nasa CR-172,227

NASA CR 172227

NASA-CR-172227
19840009490

Embedded Gage Impact Study

S.W. SCHRAMM and I.M. DANIEL

IIT Research Institute
Chicago, IL 60616

NASA Contract NAS1-16763
January 1984

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

25 1 1 RN/NASA-CR-172227
DISPLAY 25/2/1
84N17558*# ISSUE 8 PAGE 1161 CATEGORY 35 RPT#: NASA-CR-172227 NAS 1.26:172227 K06018 CNT#: NAS1-16763 84/01/00 58 PAGES UNCLASSIFIED DOCUMENT
UTTL: Embedded gage impact study TLSP: Final Contract Report, Aug. 1981 - Mar. 1983
AUTH: A/SCHRAMM, S. W.; B/DANIEL, I. M.
CORP: IIT Research Inst., Chicago, Ill. AVAIL.NTIS SAP: HC A04/MF A01
MAJS: /*DEFORMATION/*GRAPHITE-EPOXY COMPOSITES/*IMPACT DAMAGE/*LAMINATES
MINS: / EMBEDDING/ STRAIN GAGES/ ULTRASONIC TESTS
ABA: S.L.
ABS: Impact damage in graphite/epoxy laminates was characterized and transient strain history during impact was correlated. The material investigated was AS-4/3501-6 graphite/epoxy. Eight-ply and sixteen-ply quasi-isotropic laminates of 45/0/-45/90 sub s and 45/0/-45/90 sub 2s layups were fabricated with strain gages embedded between plies during the strain gages and leads from the highly conductive graphite fibers. The specimens were circular plates 12.7 cm (5 in.) in diameter and clamped along their circumference. The specimens were impacted with a 185 gm impactor, dropped from heights of 1.20 m and 1.65 m. An accelerometer was attached to the back surface of the specimen opposite the impact point and was used to trigger the recording instrumentation. The transient strain data were

1. Report No. NASA CR 172227	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EMBEDDED GAGE IMPACT STUDY		5. Report Date January 1984
		6. Performing Organization Code K06018
7. Author(s) S. W. Schramm and I. M. Daniel		8. Performing Organization Report No.
9. Performing Organization Name and Address IIT Research Institute, 10 West 35th Street, Chicago, IL 60616		10. Work Unit No.
		11. Contract or Grant No. NAS 1-16763
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration, Langley Research Center, Hampton, VA 23665		13. Type of Report and Period Covered Contract Report August 1981 - March 1983
		14. Sponsoring Agency Code
15. Supplementary Notes Langley Technical Monitor: Dr. Walter Illg Final Report		

16. Abstract

The objective of the program was to characterize impact damage in graphite/epoxy laminates and correlate it with transient strain history during impact. The material investigated was AS-4/3501-6 graphite/epoxy. Eight-ply and sixteen-ply quasi-isotropic laminates of $[45/0/-45/90]_s$ and $[45/0/-45/90]_{2s}$ layups were fabricated with strain gages embedded between plies during the strain gages and leads from the highly conductive graphite fibers. The specimens were circular plates 12.7 cm (5 in.) in diameter and clamped along their circumference. The specimens were impacted with a 185 gm impactor, dropped from heights of 1.20 m and 1.65 m. An accelerometer was attached to the back surface of the specimen opposite the impact point and was used to trigger the recording instrumentation. The transient strain data were recorded with an eight-channel waveform digitizer capable of sampling data at 0.5 μs intervals. The data were stored, processed, and plotted by means of a microcomputer. Transient strain data were correlated with results from ultrasonic inspection of the specimens.

17. Key Words (Suggested by Author(s))	18. Distribution Statement Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

N-305

n-84-17558#

FOREWORD

This is a final report on IIT Research Institute Project No. K06018 (formerly M06097), Embedded Gage Impact Study," prepared by IITRI for NASA Langley Research Center under Contract No. NAS1-16763. The work described in this report was conducted during the period 20 August 1981 to 31 March 1983. Dr. Walter Illg of NASA was the project engineer. Dr. I. M. Daniel (formerly of IITRI) was the initial principal investigator succeeded later by Mr. S. W. Schramm of IITRI. Additional contributions to the work reported herein were made by Mr. W. G. Hamilton (formerly of IITRI) and Mr. T. Niiro. Use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont.)

1. INTRODUCTION

The ever expanding structural applications of composites expose them to a variety of environments and loading conditions. One important area is the behavior of composites under localized impact loading. Impact velocities can range from low (3-6 ms^{-1}; 10-20 ft/sec), for the case of tools or other objects falling onto the composite, to intermediate (15-60 ms^{-1}; 50-200 ft/sec) velocities encountered by aircraft in flight, to high velocity ballistic impacts. The range of interest in this program was the low to intermediate one for which the damage caused in the composite is invisible to the unaided eye. The damage caused is not only a function of the velocity of impact, but also of the mass of the projectile, its geometry, and the material and layup of the composite laminate.

Impact studies on composites have been conducted by many investigators.[1-9] Nonvisible internal damage in composite laminates has been produced by dropping weights of approximately 4.5 to 9N (1 to 2 lb) from heights of 0.61 to 1.22 m (2 to 4 ft).[10] Steel, ice, and gelatin projectiles have been used at impact velocities of 31 to 305 ms^{-1} to study the foreign object damage (FOD) resistance of graphite/epoxy, boron epoxy, Kevlar/epoxy, and graphite/polyimide.[6] Similar studies have been conducted using silicon rubber projectiles at velocities up to 250 ms^{-1} (820 ft/sec).[7,9]

In references 7 and 9, unidirectional $[0_{16}]$ and $[0_2/\pm45]_{2s}$ boron/epoxy and graphite/epoxy laminates were instrumented with surface and embedded strain gages, impacted with 7.9 mm (0.31 in.) diameter silicon rubber spheres normally and obliquely (at 45 deg), and ultrasonically inspected before and after impact. The residual stiffness and strength of the material at the point of impact were measured.

The objective of this program was to use the experimental techniques developed in References 7 and 9 study the case of low velocity impact damage in graphite/epoxy composite laminates. A specific objective of the investigation was to characterize impact damage and correlate it with strain and deformation histories during impact.

2. EXPERIMENTAL PROCEDURE

2.1 SPECIMENS

2.1.1 Material Selection and Characterization

The material that was to be initially investigated was T300/5208 graphite/epoxy from NARMCO Materials, Inc. Upon receipt of the 15.2 cm (6 in.) wide prepreg tape, characterization of the material commenced.

The characterization consisted of the fabrication and testing of unidirectional coupons in tension and compression, in the longitudinal and transverse directions. Ten-degree off-axis coupons were also tested for determination of in-plane shear properties.

Longitudinal tensile and compressive properties which are fiber dominated were found acceptable for the T300/5208 prepreg. However, all matrix dominated properties were unusually low and the material was rejected. Replacement material was requested, but delivery schedules were unacceptable and a new supplier was contacted for a new material.

The T300/5208 graphite/epoxy was replaced with AS-4/3501-6 graphite/epoxy prepreg tape 30.5 cm (12 in.) wide manufactured by Hercules, Inc. The AS-4/3501-6 conforms to Specification MMS-549, Rev. B and was determined to be adequate for the program.

The AS-4/3501-6 prepreg had to be qualified and characterized before impact specimens were made. The qualification testing, 15- and 16-ply, unidirectional plates, were fabricated and then cut into:

- 6 beam specimens 10.2 cm (4 in.) long x 1.3 cm (0.5 in.) wide for flexural testing

- 6 short beam specimens 1.5 cm (0.6 in.) long x 0.4 cm (0.25 in.) wide for three point interlaminar shear testing.

The results of the qualfcation tests are shown in Table 1 for flexure and Table 2 for shear, respectively. The results agreed well with product data supplied by Hercules and the material was accepted.

TABLE 1. QUALIFICATION FLEXTURE TESTS FOR AS-4/3501-6 GRAPHITE/EPOXY

Specimen Number	Thickness cm (in.)	Width cm (in.)	Flexural Strength MPA (ksi)
1	0.191 (0.075)	1.273 (0.501)	1818 (263)
2	0.173 (0.068)	1.285 (0.506)	1880 (272)
3	0.185 (0.073)	1.283 (0.505)	1750 (254)
4	0.185 (0.073)	1.273 (0.501)	1987 (288)
5	0.178 (0.070)	1.280 (0.504)	1886 (273)
6	0.193 (0.076)	1.265 (0.498)	1826 (265)
Average:			1857 (269)

TABLE 2. QUALIFICATION INTERLAMINAR SHEAR TESTS
FOR AS-4/3501-6 GRAPHITE/EPOXY

Specimen Number	Thickness cm (in.)	Width cm (in.)	Shear Strength MPa (ksi)
1	0.211 (0.083)	0.638 (0.251)	116.7 (16.9)
2	0.203 (0.080)	0.638 (0.251)	122.4 (17.7)
3	0.216 (0.085)	0.643 (0.253)	114.3 (16.6)
4	0.211 (0.083)	0.635 (0.250)	116.0 (16.8)
5	0.206 (0.081)	0.640 (0.252)	117.9 (17.1)
		Average:	117.4 (17.0)

Unidirectional 6-ply and 8-ply plates were fabricated for material characterization. The following cure schedule was used:

- Place layup in autoclave
- Apply full vacuum
- Raise temperature at 2.8°K (5°F) per minute to 383°K (230°F)
- Hold at 383°K (230°F) for 30 minutes
- Apply 690kPa (100 psi) pressure
- Release vacuum
- Raise temperature at 2.8°K (5°F) per minute to 448°K (350°F)
- Hold for two hours at 448°K (350°F) under pressure
- Lower temperature to 367°K (200°F) at 2.8°K (5°F) per minute
- Release pressure and remove layup
- Post cure for 4 hours at 448°K (350°F) in an air circulating oven.

The density of the cured material was measured as

$$\rho_c = 1{,}614 \text{ kg/m}^3$$

from which the fiber volume ratio was computed as:

$$V_f = \frac{\rho_c - \rho_m}{\rho_f - \rho_m} = \frac{1614 - 1270}{1800 - 1270} = 0.65$$

where f = fiber density

m = matrix density.

Unidirectional tensile 0-deg properties were obtained by testing 1.27 cm x 22.9 cm (0.5 in. x 9 in.) 6-ply coupons. Unidirectional tensile 90-deg properties were obtained by testing 2.5 cm x 22.9 cm (1 in. x 9 in.) 8-ply and 16-ply coupons. Compressive properties were obtained by testing 16-ply coupons, 13.5 cm x 0.6 cm (5.3 in. x 0.25 in.) in the IITRI compression fixture. In-plane shear properties were determined by testing 10-deg off-axis specimens. The coupons were 1.27 cm (0.5 in.) wide x 25.4 cm (10 in.) long and 6-plies thick. They were instrumented with one 3-gage rosette on each side. Two to four specimens were tested in every case. The results are shown in Table 3.

TABLE 3. PROPERTIES OF UNIDIRECTIONAL GRAPHITE/EPOXY AS-4/3501-6

Property	Value
Ply Thickness	0.127 mm (0.005 in.)
Longitudinal Modulus, E_{11}	159.4 GPa (23.1 x 10^6 psi)
Transverse Modulus, E_{22}	10.6 GPa (1.54 x 10^6 psi)
Shear Modulus, G_{12}	8.2 GPa (1.19 x 10^6 psi)
Major Poisson's Ratio, ν_{12}	0.28
Minor Poisson's Ratio, ν_{21}	0.02
Longitudinal Tensile Strength, F_{1T}	1980 MPa (287 ksi)
Ultimate Longitudinal Tensile Strain, ε^u_{11T}	0.0122
Longitudinal Compressive Strength, F_{1C}	1440 MPa (209 ksi)
Ultimate Longitudinal Compressive Strain, ε^u_{11C}	0.0141
Transverse Tensile Strength F_{2T}	43.1 MPa (6.2 ksi)
Ultimate Transverse Tensile Strain, ε^u_{22T}	0.0039
Transverse Compressive Strength, F_{2C}	228 MPa (33 ksi)
Ultimate Transverse Compressive Strain, ε^u_{22C}	0.0239
In-plane Shear Strength, F_6	56.4 MPa (6.0 ksi)
Ultimate Shear Strain, ε^u_{12}	0.0027

2.1.2 Preliminary Impact Testing

Preliminary tests were conducted to determine approximate limits for the acceleration and strain data to be obtained later. The specimen geometry was the same as for the final testing with embedded gages (Figure 1).

These specimens were formed by bonding a 15.2 cm (6 in.) square graphite/epoxy laminate between two 1.3 cm (0.5 in.) thick aluminum plates with a 12.7 cm (5 in.) diameter cutout. Though not shown in Figure 1, the aluminum plates were held together with socket head cap screws torqued to a common value during the adhesive curing period. The cap screws were removed from the specimen before impact testing. Two types of specimens were fabricated which were 8-ply and 16-ply of $[45/0/-45/90]_s$ and $[45/0-45/90]_{2s}$ layups. No embedded gages were used in these preliminary specimens. In the first specimen two gages were applied on the back surface of the specimen at a distance of 3.2 mm (0.125 in) from the center in the radial direction. In subsequent specimens only one gage was applied on the back surface directly under the impact point. Specimens were impacted repeatedly and the transient strain recorded in every case. At the end of a series of impact loadings each specimen was scanned ultrasonically.

The first specimen was a $[45/0/-45/90]_s$ laminate and was impacted with a 185 gm (0.085 lb) impactor released from a height of 122 cm (48 in.). Figure 2 shows the acceleration and strain records obtained. In Figure 2b, the period of deceleration (from 0 to approximately 1.2 msec) corresponds to the time between initial contact and maximum penetration and/or deformation of the target. During this period, the strains at the two gage locations increase monotonically to a maximum at approximately 1.5 msec after impact. The strain curves lag behind the acceleration curve because the strain gages were not located at the center of the impact and were on the surface opposite to that where the impactor contacted the specimen. In the period between 1.2 and 2.5 msec from impact, the rate of change of acceleration becomes positive and the strain decreases. A visual inspection of the specimen after impact showed no visible damage. These preliminary tests showed that measurable (approximately 8000 $\mu\varepsilon$) strains can be generated with no visible damage to the specimen.

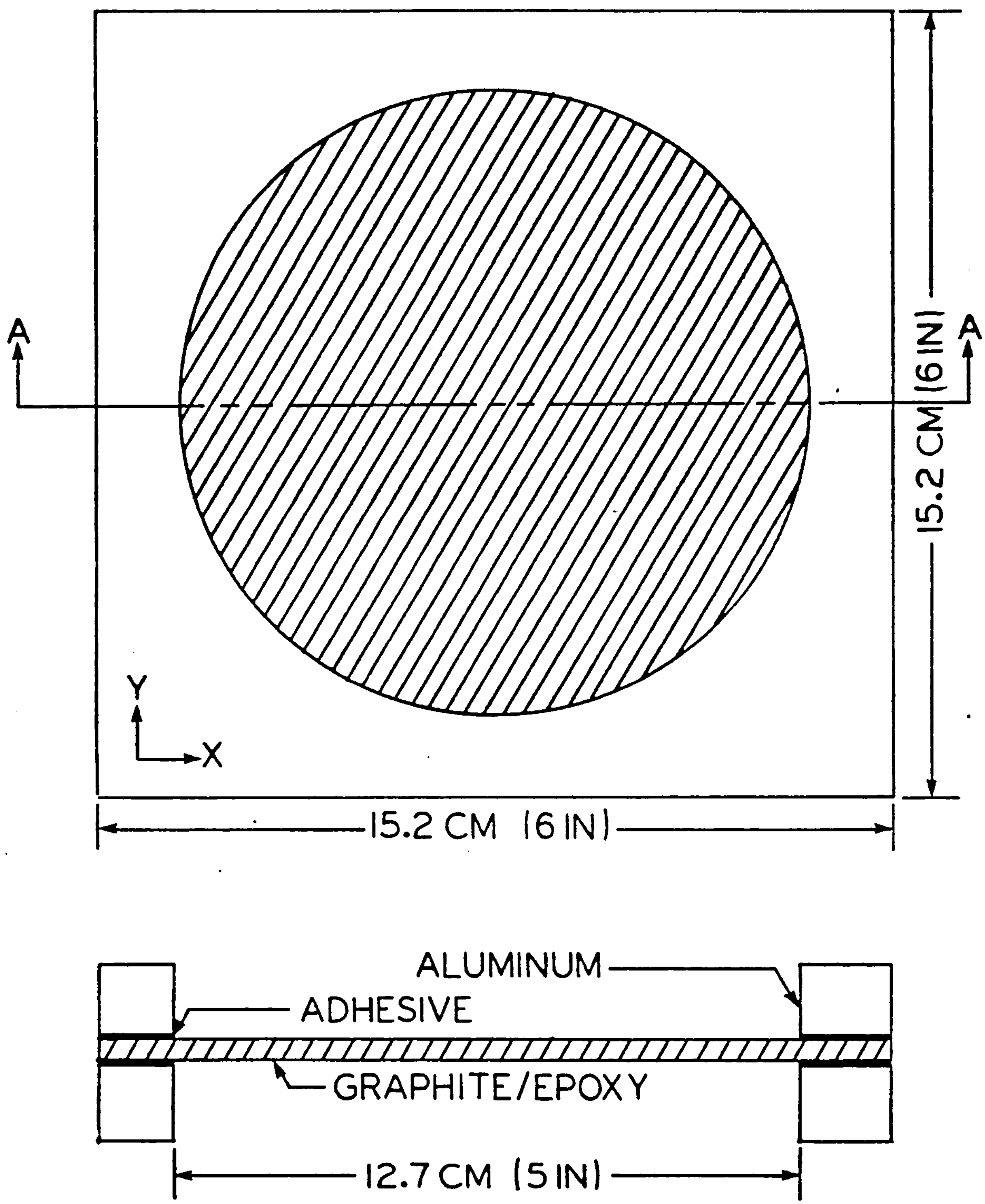
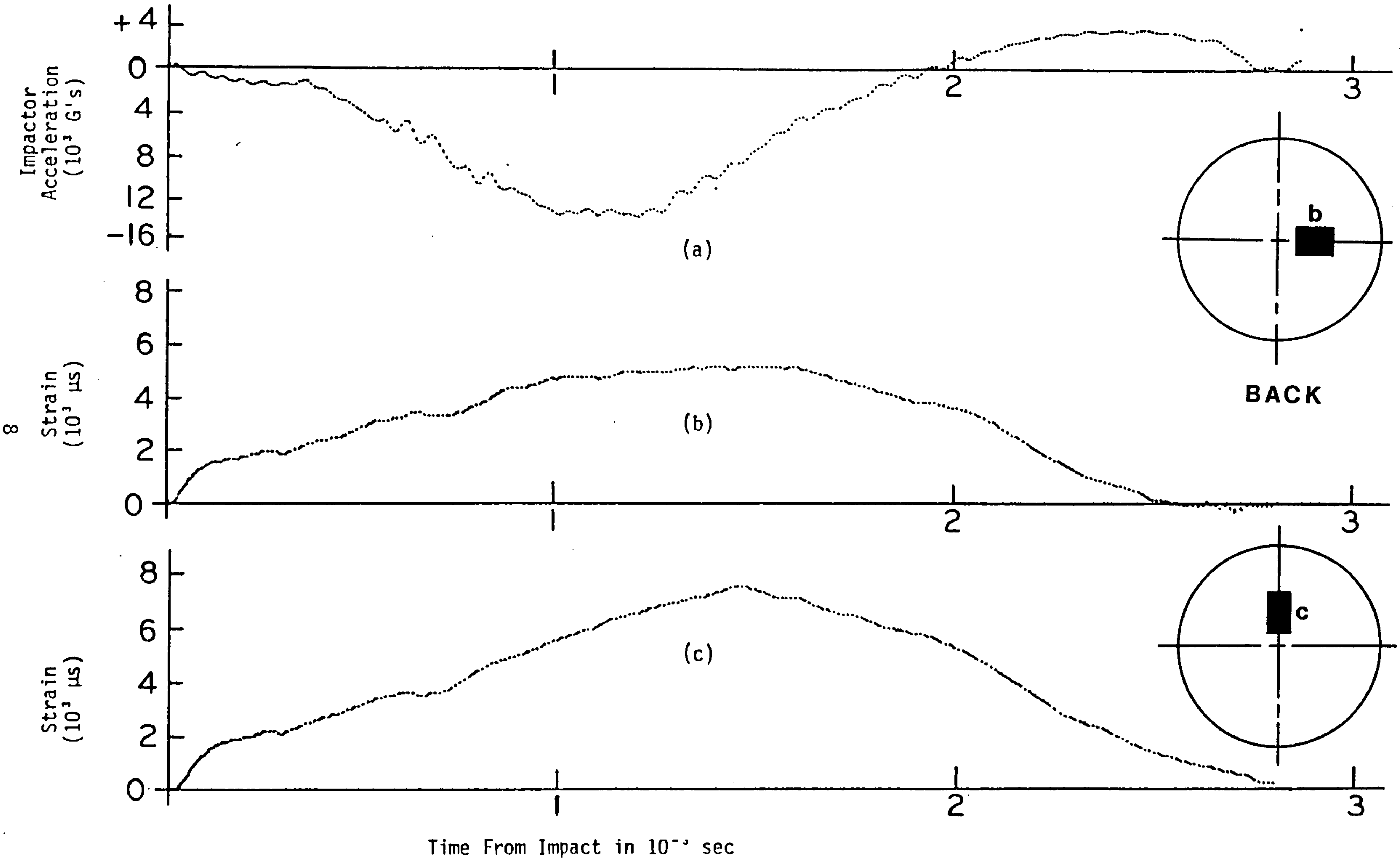


Figure 1. Configuration of preliminary impact specimen.



8

Figure 2. Acceleration (a) and strain (b and c) histories for 122 cm (48 in.) drop of a 185 gm (0.085 lb) impactor onto an 8-ply $[45/0/-45/90]_s$ graphite/epoxy plate 15.2 cm (6 in.) square. Gages (b) and (c) approximately equidistant from impact location. (Preliminary specimen No. 1).

Figure 3 shows the transient strain records for another $[45/0/-45/90]_s$ graphite/epoxy laminate impacted from heights of 83.8 cm (33 in.) and 91.4 cm (36 in.) by a 185.3 gm (0.41 lb) impactor. Peak strain was reached at approximately 1.3 ms after impact and the total duration of the main strain pulse was approximately 2.7 ms. The peak strain initially is approximately 5×10^{-3} and it declines steadily with repeated impacts from approximately the same height. This may be due to the damage being accumulated in the impacted area which would tend to cushion the impact somewhat and to the material degradation itself. An ultrasonic C-scan after nine impacts shows extensive damage around the area of impact (Figure 4). It is possible that this damage consists primarily of matrix cracking and delamination but no fiber fractures as the peak strain was always below the ultimate strain in the fiber direction. Similar tests were conducted with other 8-ply specimens. The resulting strain histories were inconsistent with the drop heights, but the final damage was extensive in all cases after a number of impacts. Ulrasonic C-scans for these specimens after 6, 13, and 2 impacts, respectively, are also shown in Figure 4.

Figure 5a shows the transient strain record for the first drop of the impactor on a $[45/0/-45/90]_s$ laminate. The peak strain of approximately 1.4×10^{-3} is reached at approximately 1.2 ms after impact. The duration of the primary strain pulse is somewhat shorter than that in the case of the 8-ply laminates. The extensive damage detected after only two impacts is consistent with the large peak strain recorded (Figure 5b).

Based on these preliminary tests, it was decided to test subsequent specimens by impacting the 185 gm impactor from heights of 120 cm (47.2 in.) and 165 cm (65 in.) for the 8-ply and 16-ply specimens, respectively.

2.1.3 Embedded Gage Specimens

Fabrication of the graphite/epoxy laminate specimens for this project presented some difficulties. The difficulties arose primarily from two sources; the first was the number of gages to be embedded into the laminates, and the second was the electrical conductivity of the graphite/epoxy composite. These problems could be resolved only by developing a rigorous and time consuming specimen fabrication procedure.

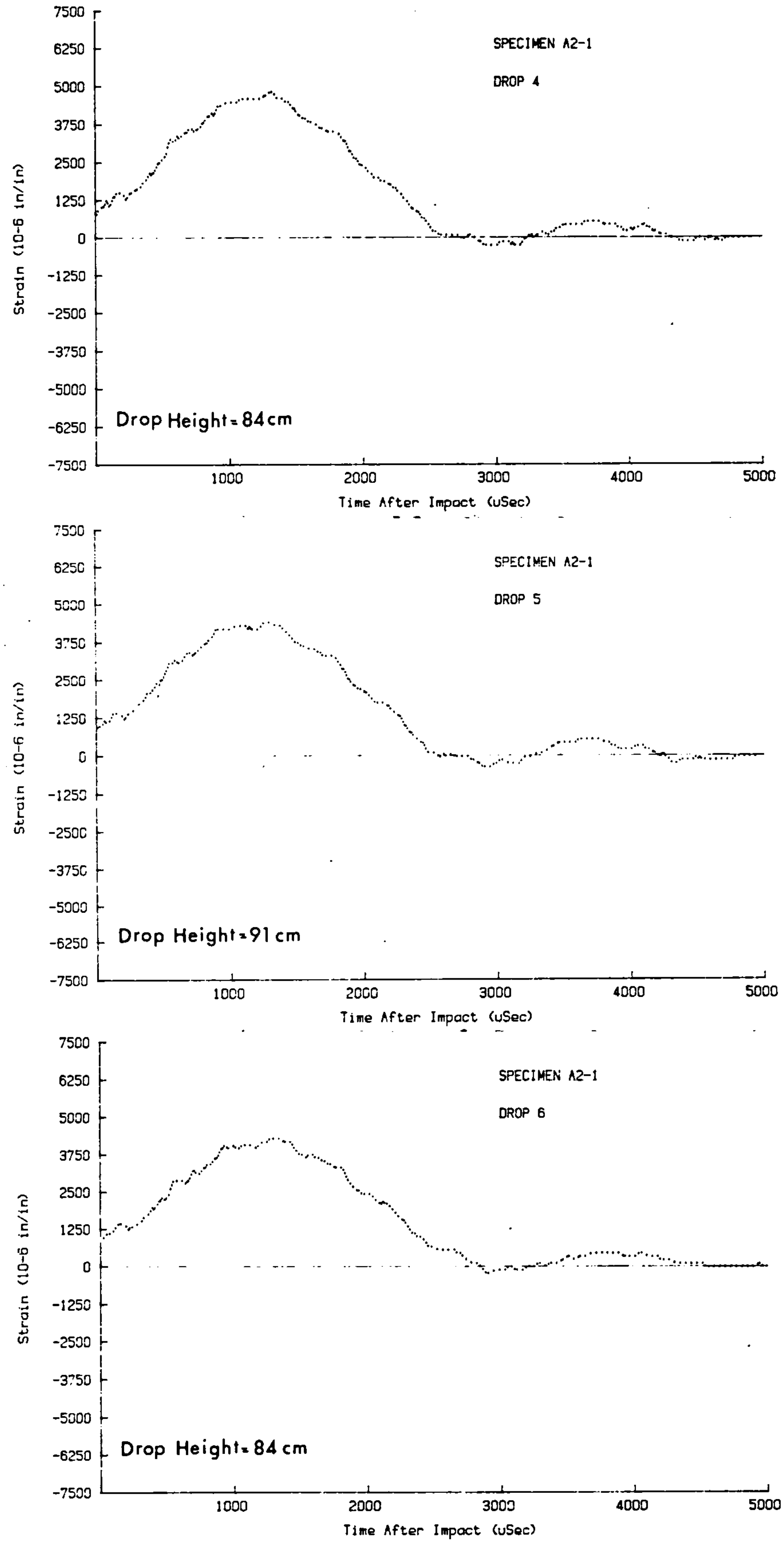


Figure 3. Transient strain in $[45/0/-45/90]_s$ laminate during successive impacts of 185 gm impactor.

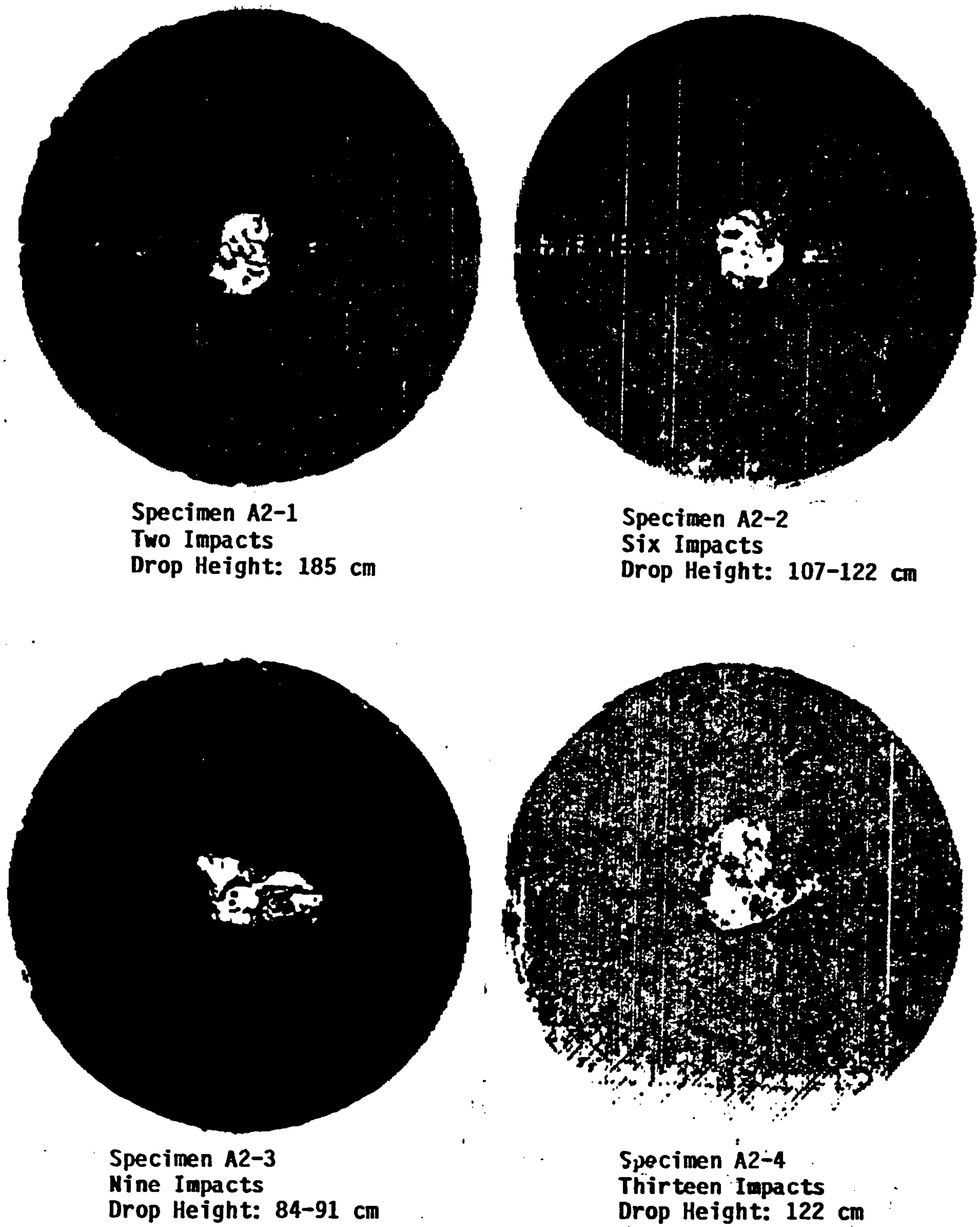


Figure 4. Ultrasonic C-scans for $[45/0/-45/90]_s$ laminate after repeated impacts with 185 gm impactor.

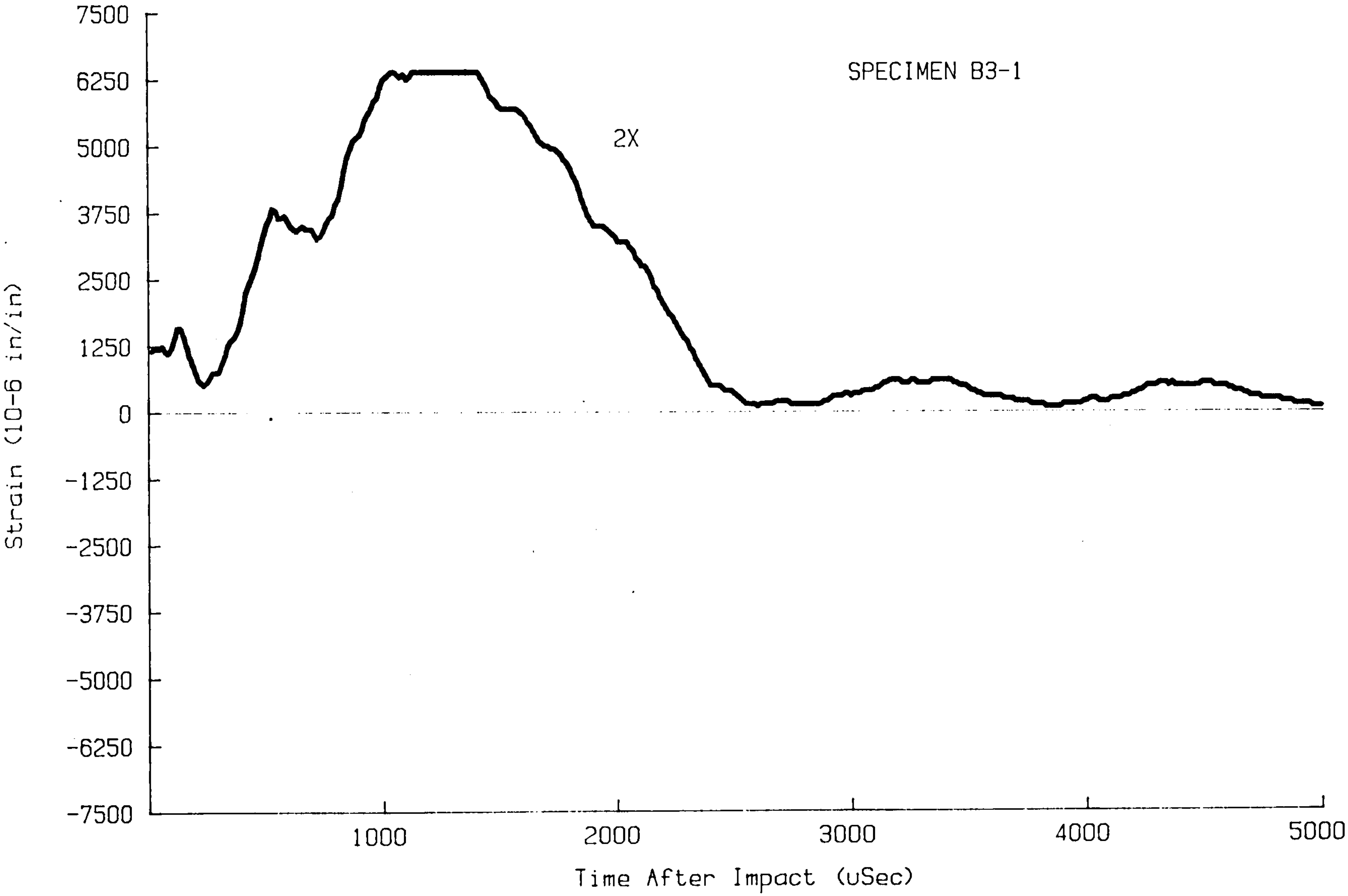


Figure 5a. Transient strain in $[45/0/-45/90]_s$ laminate during impact of a 185.3 gm impactor dropped from a height of 165.1 cm (65 in.).

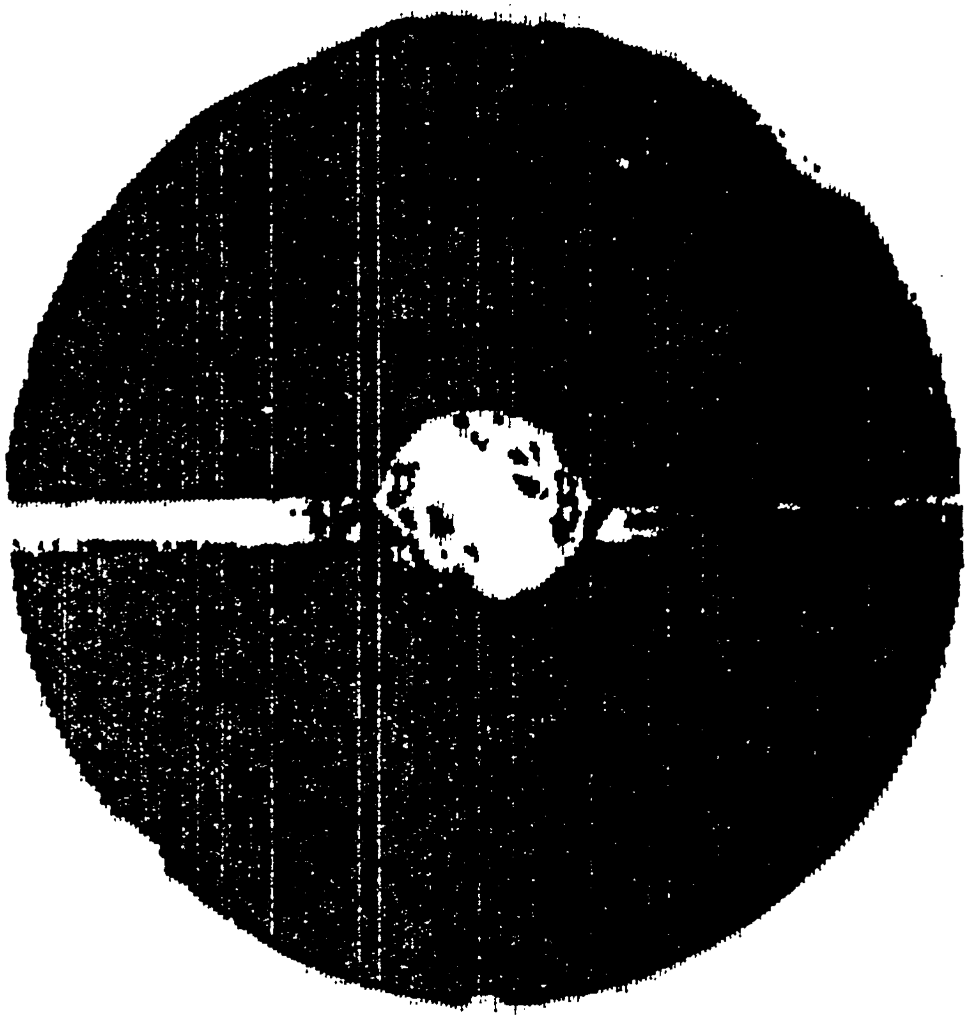


Figure 5b. Ultrasonic C-scan for $[45/0/-45/90]_s$ laminate aftertwo impacts of a 185.3 gm (0.41 lb) impactor from a height of 165.1 cm (65 in.).

As was mentioned previously, a special fabrication procedure was developed for preparing the embedded gage specimens. Two points were obvious immediately. The first was that there would have to be some provision made so the gage-to-wire solder connection would be insulated to prevent grounding of the gage to the specimen. The second point was that an insulated ribbon type lead wire would have to be used from the free edge of the laminate to the embedded gage to minimize the thickness variation of the laminate.

The first specimen was fabricated with epoxy-phenolic resin encapsulated gages with the solder connections sandwiched between two pieces of Kapton film. The problem with this configuration was that the gage was nearly impossible to position and would migrate during the laminate cure. When the gage would migrate, it would strain the solder connections and in many cases, would cause a break in the connection grounding the gage. The gage became useless because there was no way to reattach the leads to the connectors.

The second specimen was fabricated using open-face gages with both grid and connectors sandwiched in Kapton film. These gages reacted similarly to those of the first specimen in that two of the embedded gages shifted during the cure cycle. The shift was far enough that either one or both of the solder connections broke.

The third and fourth specimens were fabricated by encapsulating the gage and solder connections in the same epoxy that was used in making the prepreg. A supply of resin was sent to IITRI by Hercules for this purpose. The gages worked well before being layed up in the laminate, but inconsistently after the laminate was cured. What is suspected is that the encapsulating epoxy softened during the laminate cure allowing the graphite fibers to penetrate the encapsulation to where the fibers would intermittently touch the solder connections causing the gage to ground out occasionally. The first four specimens fabricated did have a number of embedded gages which worked well, but not of a number and location that would generate any amount of useful data. These four specimens were used as practice specimens for multiple drop tests.

The gage embedment technique which proved to be the most successful was a two step process. The first step was to encapsulate the strain gage. The second step was to locate the strain gage in the layup and cure the laminate. Although this sounds identical to the previously described technique, there was one major difference; the encapsulation was oven cured before being layed up in the laminate. In the other encapsulation technique, the epoxy was only air cured in the hope that the strain gage would remain somewhat flexible thereby integrating better into the epoxy matrix of the laminate. Since this was not the case, it was decided that the next best option would be to cure the encapsulation before layup. The strain gage was wired with ribbon leads soldered at the tabs. The wired gage was then coated with a uniform thickness of epoxy on both sides. The coated gage was placed in a sandwich of glass scrim cloth. The sandwich was then cured under vacuum in an air circulating oven. After curing, the gage was ready for insertion in the layup. As the laminate was layed up, the encapsulated gages were located and held in place by being "tack glued" into place using a couple of drops of epoxy on both sides of the gage. Since the laminate was cured under vacuum/pressure conditions, the excess epoxy from the prepreg and the tacking was drawn into the bleeder cloth, leaving the laminate relatively unaffected by the presence of the strain gages. After the laminates were cured and post cured, they were bonded to the aluminum holding fixtures. Subsequently, external strain gage lead wires were soldered into place at external connectors mounted onto the aluminum plates. The external lead wires were soldered onto the free ends of the ribbon leads which were left protruding from the edges of the laminate plates.

The total number of acceptable test specimens was four; two 8-ply $[45/0/-45/90]_s$ and two 16-ply $[45/0/-45/90]_{2s}$. The gage layout is shown in Table 4 and illustrated in Figures 6, 7, 8 and 9. In the gage layout table, R indicates a radial gage and T indicates a transverse gage. A radial gage is defined as one having the grid parallel to a radial line from the center of the specimen; a transverse gage is one having the grid perpendicular to a similar radial line. The 125AD type gage (referred to the Micro-Measurements catalog numbers) is a single gage with a 3.18 x 3.18 mm (0.125 x 0.125 in.) grid area.

TABLE 4. GAGE LAYOUT FOR SPECIMENS WITH EMBEDDED GAGES

Specimen No.	Layout	Gage No.	Type	x, cm (in.)	y, cm (in.)	Plies from Top
A5-2	$[45/0/-45/90]_s$	1R	125AD	0	0	8
		2R	"	-1.27 (0.5)	0	8
		3R	"	2.54 (1.0)	0	8
		4R	"	0	-5.08 (2.0)	8
		5R	"	0	0	4
		6R	"	-1.27 (0.5)	0	6
		7R	"	2.54 (1.0)	0	7
		8R	"	-3.81 (1.5)	0	8
		9R	"	-1.27 (0.5)	0	0
		10R	"	2.54 (1.0)	0	0
		11R	"	0	-5.08 (2.0)	0
A6-1	$[45/0/-45/90]_s$	1R	125AD	0	0	2
		2R	"	0	0	6
		3R	"	0	0	8
		4R	"	1.27 (0.5)	0	2
		5R	"	1.27 (0.5)	0	6
		6R	"	1.27 (0.5)	0	8
		7T	"	-2.54 (1.0)	0	0
		8T	"	-2.54 (1.0)	0	4
		9T	"	-2.54 (1.0)	0	8
		10T	"	0	-1.27 (0.5)	8
		11T	"	0	-1.27 (0.5)	6

TABLE 4. GAGE LAYOUT FOR SPECIMENS WITH EMBEDDED GAGES (concluded)

Specimen No.	Layout	Gage No.	Type	X, cm (in.)	y, cm (in.)	Plies from Top
B5-1	$[45/0/-45/90]_s$	1R	125AD	0	-2.54 (1.0)	16
		2R	"	-1.27 (0.5)	0	16
		3R	"	2.54 (1.0)	0	16
		4R	"	0	-5.08 (2.0)	16
		5R	"	0	0	12
		6R	"	-1.27 (0.5)	0	12
		7R	"	2.54 (1.0)	0	12
		8R	"	-1.27 (0.5)	0	8
		9R	"	2.54 (1.0)	0	8
		10R	"	-1.27 (0.5)	0	0
		11R	"	2.54 (1.0)	0	0
B6-1	$[45/0/45/90]_s$	1R	125AD	0	0	4
		2R	"	0	0	8
		3R	"	0	0	12
		4R	"	0	0	16
		5R	"	1.27 (0.5)	0	12
		6R	"	1.27 (0.5)	0	16
		7T	"	-1.27 (0.5)	0	12
		8T	"	-1.27 (0.5)	0	16
		9T	"	0	-2.54 (1.0)	0
		10T	"	0	-2.54 (1.0)	8
		11T	"	0	-2.54 (1.0)	16

X = 0, Y = 0 is geometric center of graphite/epoxy plate.

R is Radial

T is Transverse

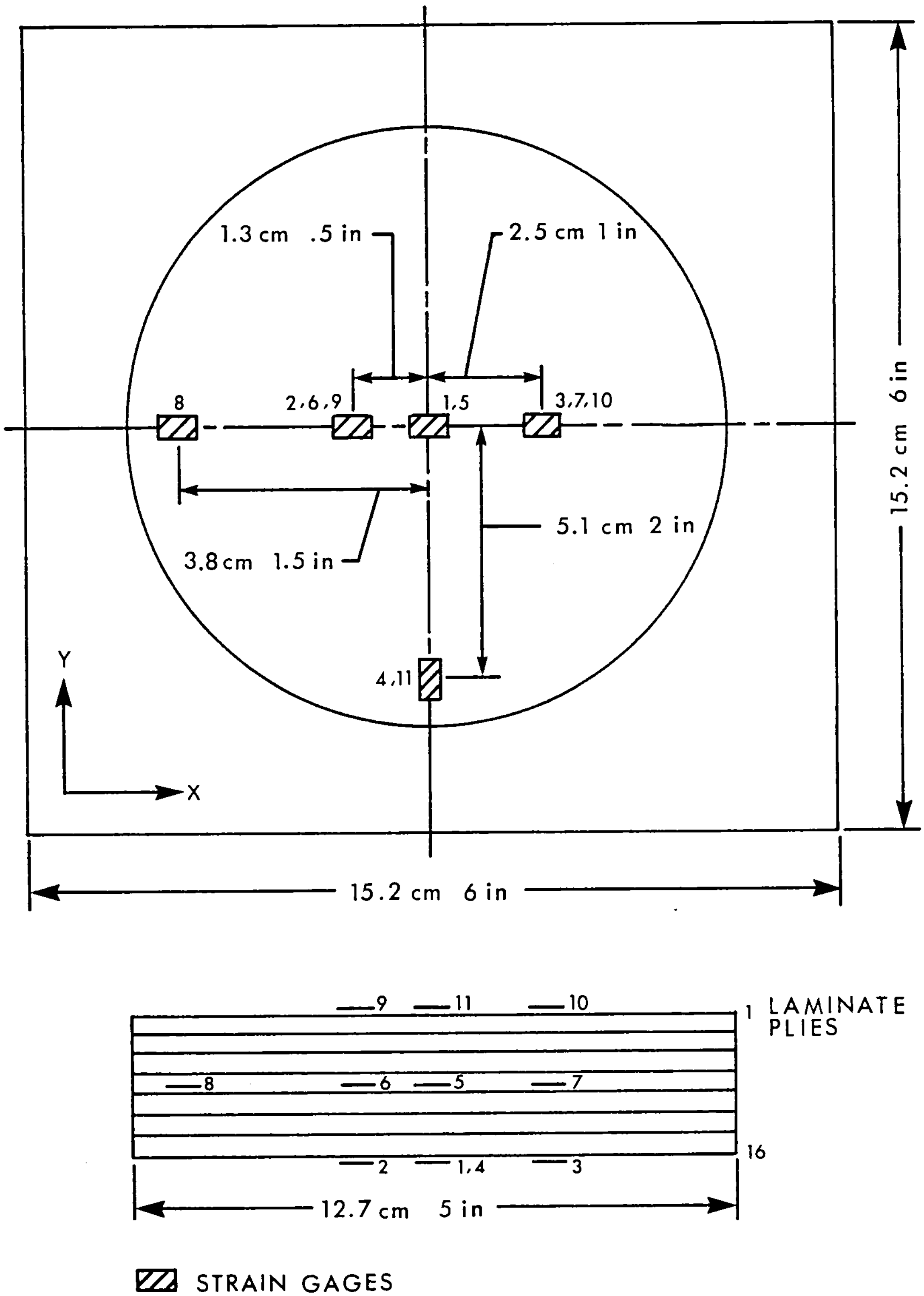


Figure 6. Gage layout for $[45/0/-45/90]_s$ specimen A5-2.

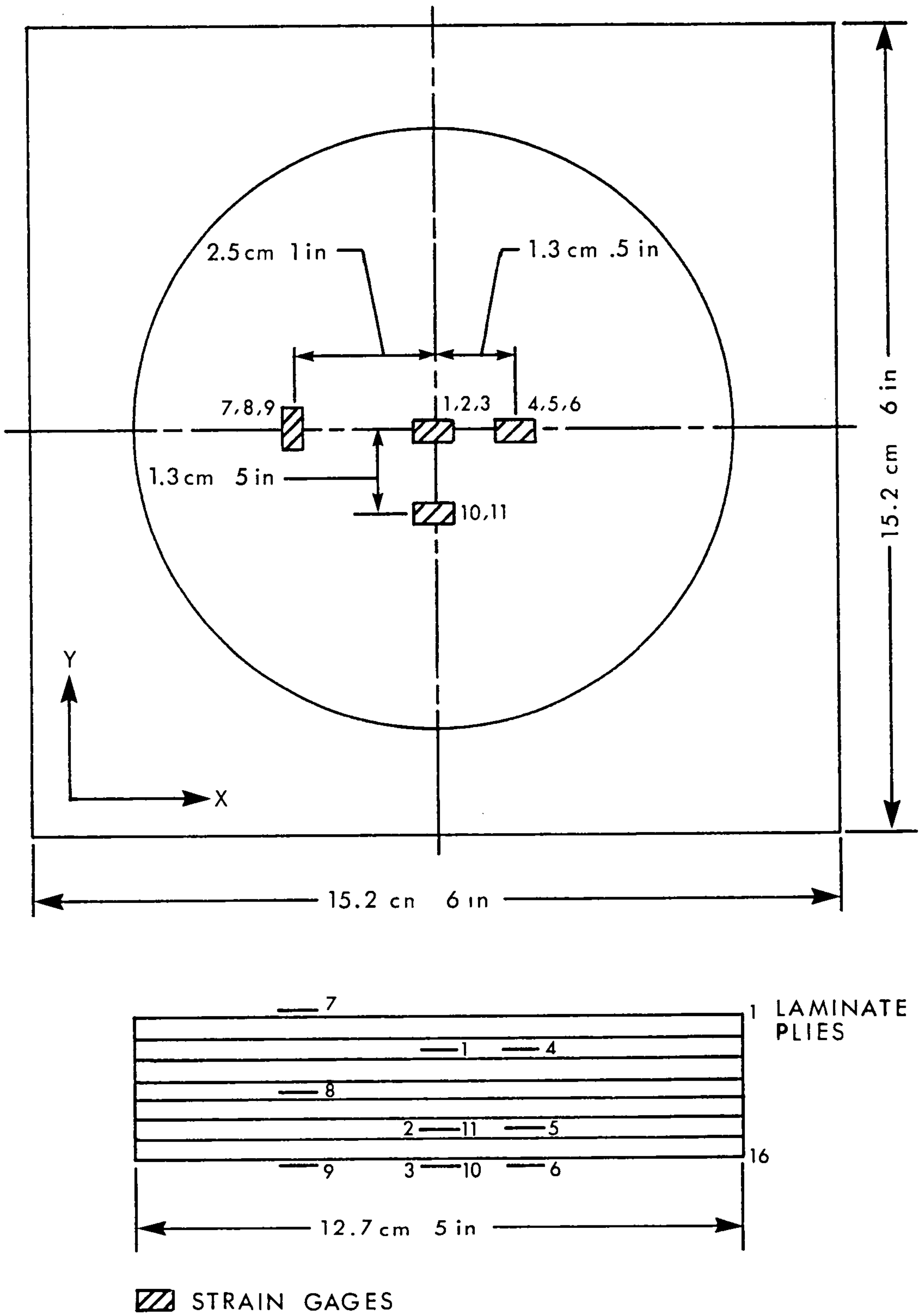


Figure 7. Gage layout for $[45/0/-45/90]_s$ specimen A6-1.

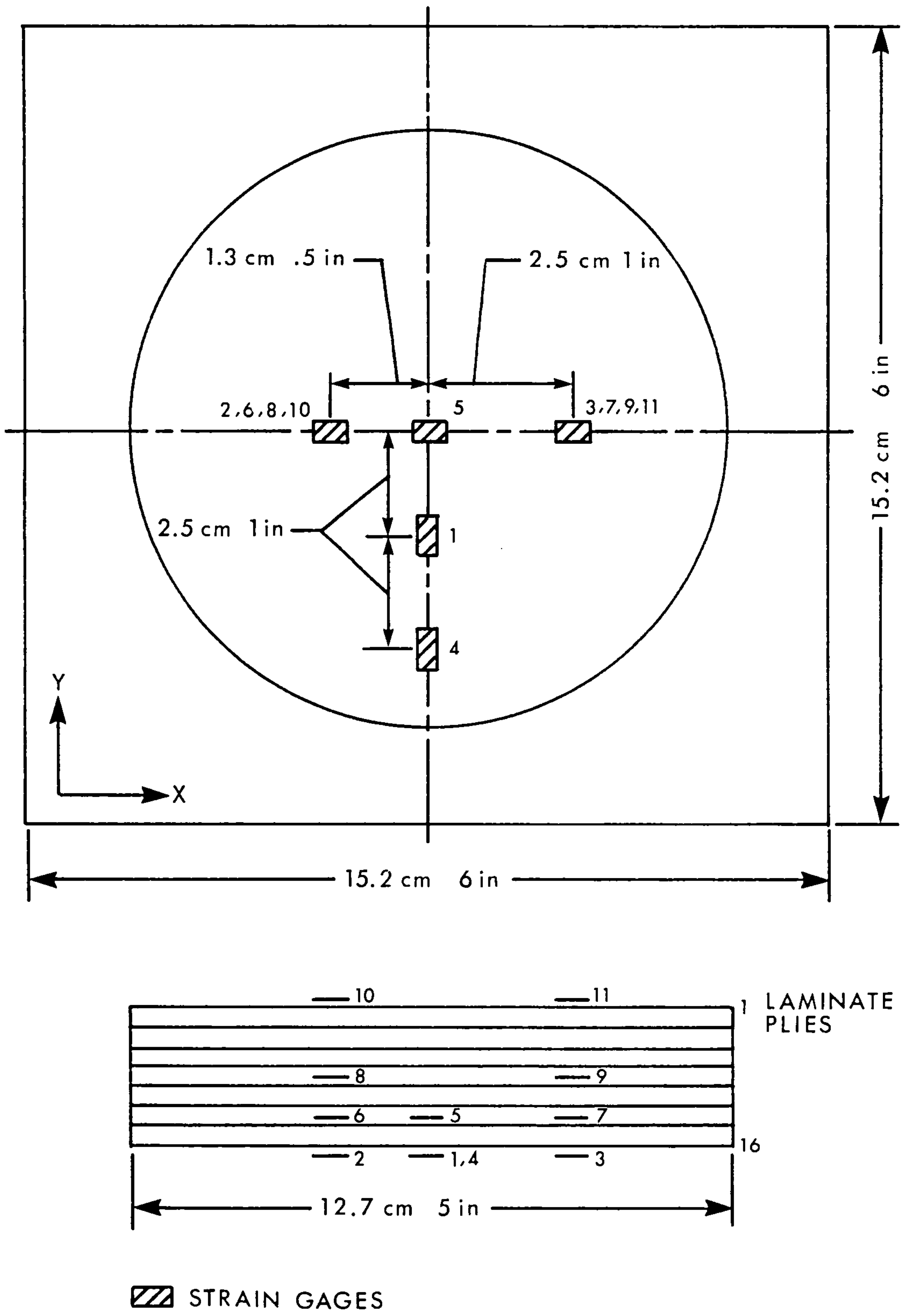


Figure 8. Gage layout for $[45/0/-45/90]_s$ specimen B5-1.

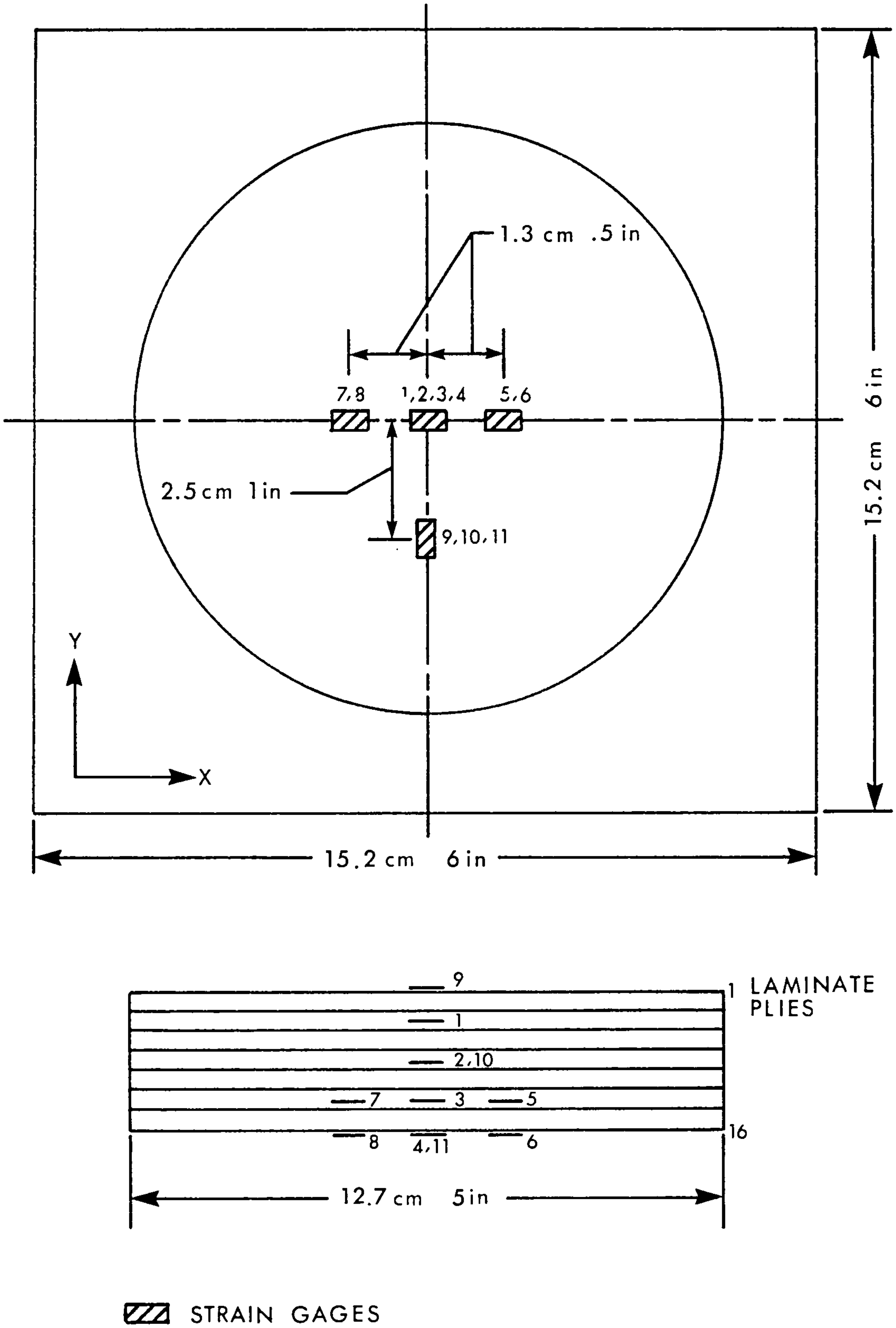


Figure 9. Gage layout for $[45/0/-45/90]_s$ specimen B6-1.

2.2 TEST EQUIPMENT

2.2.1 Drop Fixture

The falling weight fixture consisted of three elements, the guide rode, the impactor, and the specimen platform. A sketch of the fixture is shown in Figure 10. A photograph of the bottom part of the fixture is shown in Figure 11.

The guide rods were two 1.6 cm (0.625 in.) diameter, 2 m (78 in.) long, parallel steel dowels located at a distance of 5.1 cm (2 in.) center to center. The guide rods were wall mounted using specially fabricated aluminum mounting hardware. The rod mounts were fabricated with holding and adjustment set screws so the parallelism of the rods was maintained over the 183 cm (72 in.) drop length. The rods were polished and lubricated to minimize the friction losses associated with the impactor moving along the guide rods. One of the guide rods was enscribed with an elevation scale so that the drop heights could be easily determined and reproduced.

The impactor, Figure 12, consisted of five parts; the slug, two brass "v-notched" guide plates, and two slug extensions. The basic impactor consisted of the hemispherically ended steel slug and the two brass guide plates. The mass of the basic impactor was 185 gm (0.39 lb), and it was found to be adequate for producing subsurface damage in both the 8- and 16-ply laminates within the limits of the 183 cm (72 in.) drop height. The slug extensions, like the slug, were made from 1.6 cm (0.625 in.) diameter steel rod. At the trailing edge of the slug and slug extensions, holes were drilled and tapped so the extensions could be threaded onto the slug to vary the total mass of the impactor. Increasing the total mass of the impactor was the easiest way to increase the impact force given the fact that the drop height was restricted by the ceiling height of the laboratory. If increasing the mass of the impactor became too unwieldly, the back-up position was to use a compressed air cylinder to accelerate the impactor to generate an acceptable impact force.

The brass guide plates were used to stabilize the impactor as it dropped between the guide rods. The guide plates were held in place with set screws which threaded into tapped holes on the slug and extensions. The guide plates

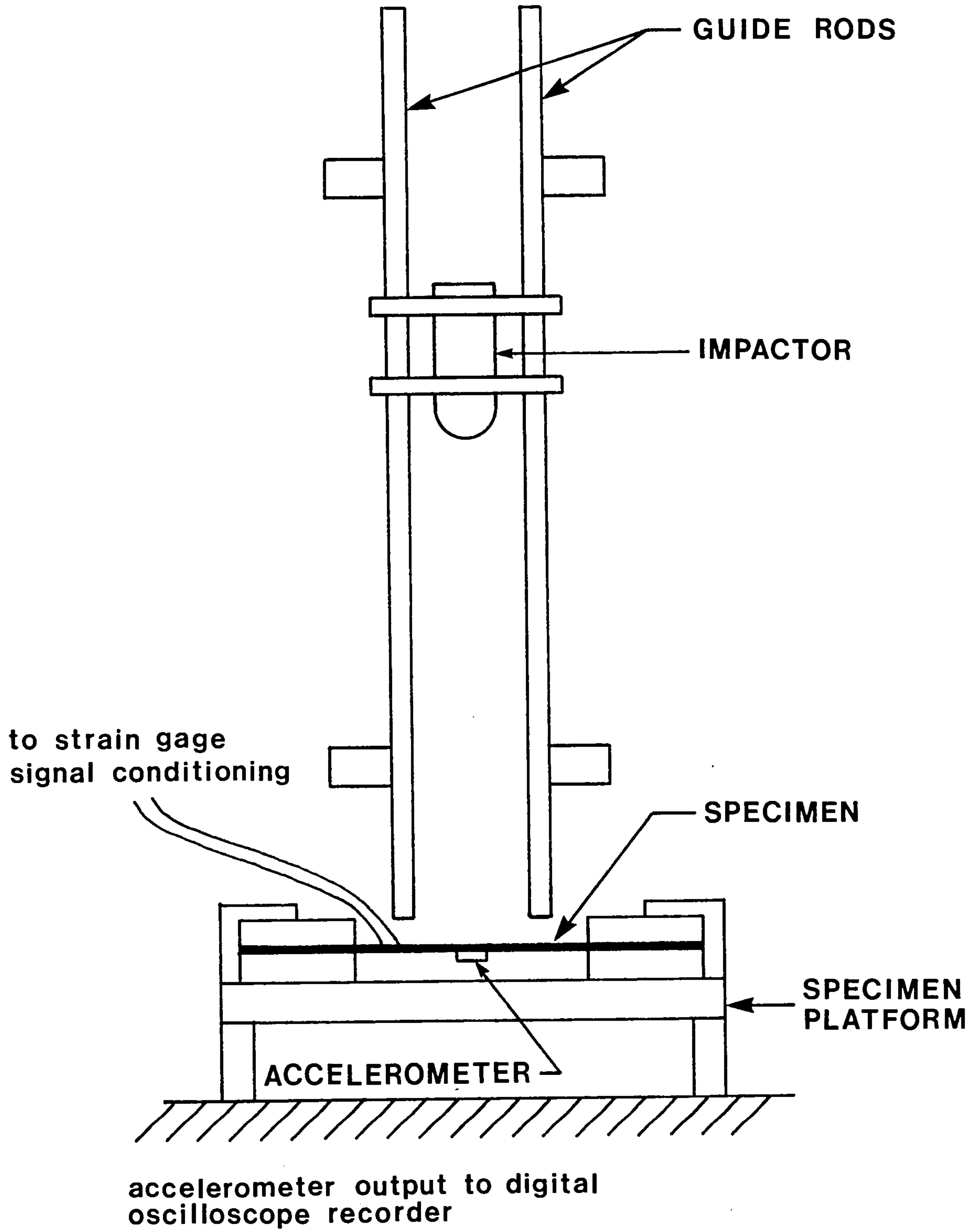


Figure 10. Sketch of drop impact fixture.

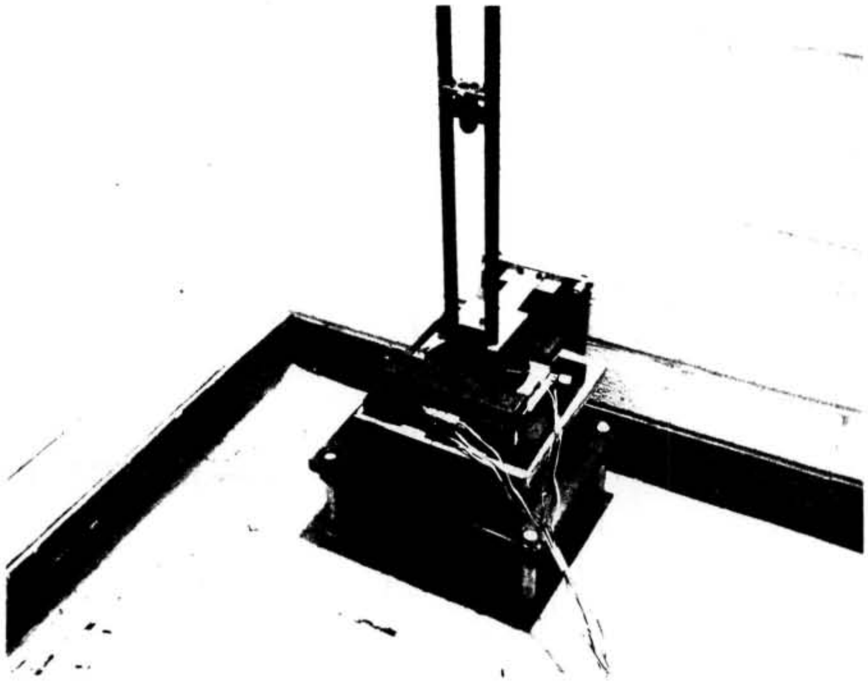


Figure 11. Drop fixture.

Figure 12. Impactor components.

were spaced to minimize the possibility of the impactor cocking and jamming between the guide rods. The "v-notches" were also sized so there was a minimum amount of contact between the guide plates and guide rods. Since the guide rods were generously lubricated before each test, there were minor friction losses associated with each impact since there was very little contact between the plates and rods.

The specimen platform consisted of an adjustable baseplate, two elevation bars, and two clamping bars. The baseplate was 25.4 x 31.8 x 1.9 cm (10 x 12.5 x 0.75 in.) steel with a threaded hole at each of the four corners. Into each hole a 15 cm (6 in.) long bolt was threaded. The bolts acted as the legs of the platform and provided height and alignment adjustment with respect to the drop fixture. The upper surface of the baseplate was inscribed with the point of impact and elevation bar locations as points of reference used during experiment set-ups.

The elevation bars were 2.5 x 5 x 15 cm (1 x 2 x 6 in.) steel gage blocks squared and ground on all surfaces. The elevation bars were used to provide coarse elevation changes for positioning the target specimens. The 15 cm (6 in.) length was selected because this was the same length as the aluminum plates bonded to the graphite/epoxy laminates. With this common length, the aluminum plate was totally supported which minimmized the deflection of the target during impact.

The clamping bars were also 2.5 x 5 x 15 cm (1 x 2 x 6 in.) steel gage blocks squared and ground on all surfaces. The clamping bars were used between the upper aluminum plate of the target and the lowest guide rod support fixture. The clamping bars were aligned normally to the elevation bars along the edge of the aluminum plate.

After the baseplate, elevation and clamping bars were positioned, the bolt legs of the baseplate were turned until the assembly was snug between the ground plane and the drop fixture. This was done to minimize impact energy losses due to the specimen deflecting or bouncing during impact.

2.2.2 Recording Instrumentation

The data acquisition/processing system, shown schematically in Figure 13, consisted of three elements; a triggering accelerometer and charge amplifier, an 8-channel waveform digitizer, and a micro-computer based data handling system. Triggering of the 8-channel waveform digitizer system was initiated using a 10 g (98 m/sec^2; 320 ft/sec^2) Endevco, piezoelectric accelerometer. The accelerometer signal was conditioned by a PCB Model 462A charge amplifier with a multiplication range of 50 to 100K. A photograph of the system is shown in Figure 14.

During the preliminary impact tests, the accelerometer was adhesively bonded to the trailing edge of the impactor slug. This worked well for the low (less than 1 m, 3 ft) drops, but caused problems at drop heights in excess of 1 m (3 ft). To provide for drops in excess of 1 m (3 ft), an extension cable had to be added between the accelerometer and the charge amplifier. In several practice drops, the extension cable was the apparent source of premature triggering of the digitizer. This problem persisted through two replacement cables and was finally resolved with a third cable. The source of the problem was that the cable was twisting while the impactor was falling, causing causing the wiring inside the cable to ground against the cable connector. The grounding would trigger the digitizer. Another problem associated with mounting the accelerometer on the impactor was the rebound of the impactor after impact. The impactor rebound was severe enough in most cases to cause the accelerometer to separate from the impactor, even though the accelerometer was adhesively bonded to the impactor. In one case, the rebound was severe enough to cause the backing shield of the accelerometer to come off of the accelerometer body. The impactor mounting location for the accelerometer was considered to be unacceptable for the final tests because premature triggering of the digitizer could not be allowed.

Two alternate accelerometer mounting positions on the target specimen were then considered. One was on the front (impacted) surface and the other was on the back side of the specimen. Both positions were tested and the back face position was selected as more preferable. Although the front face accelerometer mounting position was never a heavily considered option, because the accelerometer could not be positioned close enough to the point of impact to

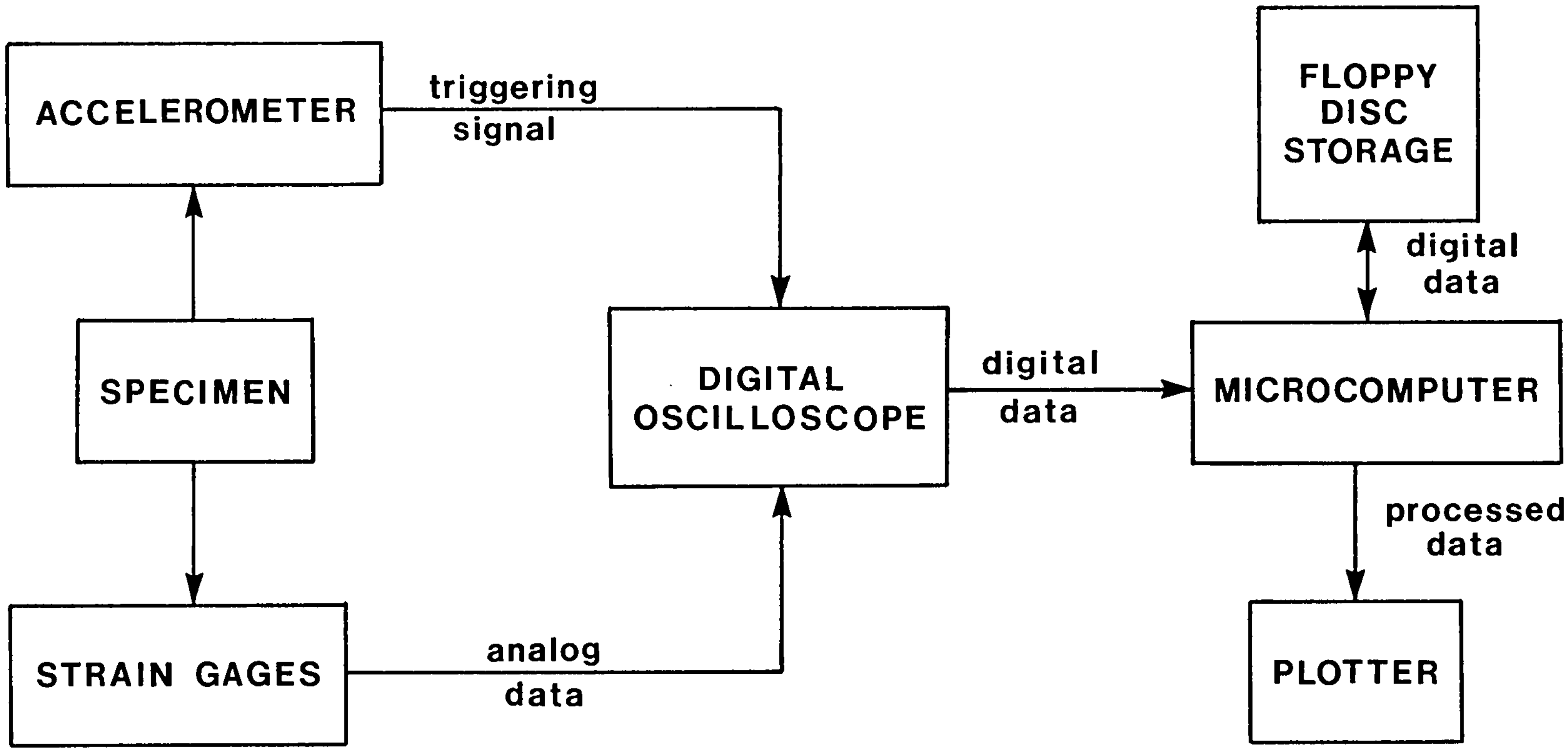


Figure 13. Schematic diagram of data acquisition and processing system.

Figure 14. Data capturing/recording/display system.

trigger the digitizer soon enough to capture the entire impact event, it was tested because it was suspected that the accelerometer might separate from the specimen due to the impact deflection without triggering the digitizer. This was not the case because in one preliminary test, the accelerometer did fall away from the specimen but still triggered the digitizer early enough to capture the entire impact event. Therefore, for the four "final" impact tests conducted, the accelerometer was adhesively bonded to the back surface of the target as close as possible to the geometric center (impact point on the upper surface) of the specimen.

The 8-channel waveform digitizer used on the program was a Gould Biomation Model 2805 Master with three Model 2805 slaves. The 2805 Master is an analog-to-digital converter with a solid-state memory that stores the equivalent of an analog signal. The Master has a simultaneous dual channel recording rate of up to 5 MHz (200 ns/point), and 2048 words of 8 bit memory per channel. Each slave unit had the same specifications as the master unit. A peripheral part of the digitizer was a digitizer interface. The interface used was a Gould Biomation Model 4880 Interface. The Model 4880 is an IEEE bus interface which provided a data transfer path between the digitizer and the microcomputer.

The microcomputer used was a Hewlett-Packard HP-85 with expanded memory to 32K. The microcomputer was supported with an HP-82092M flexible disc drive and an HP-7470A plotter. The HP-85 system was used based on system capability recommendations made by Gould, manufacturer of the digitizer. The microcomputer was initially programmed using software provided by Gould. The vendor-supplied software did not perform to the minimum requirements of the research program and had to be extensively modified. The programming was sufficient to provide error free remote initialization of the digitizer control settings, and transfer of the data to flexible data discs. Where the programming was very weak was in data display and plotting functions. As an example, there were no provisions in either the CRT display software or the plotting software to display or plot more than one data trace on a single medium. The software was modified so that up to all eight channels of captured data could be displayed or plotted on a single medium simultaneously. Other modifications made

to the software included changes in file handling routines and extensive changes in the plotter scaling and labeling routines. These modifications were unplanned but necessary in order to extract any meaningful information from the captured data.

2.2.3 Nondestructive Evaluation Equipment

One of the objectives of the program was to quantify the extent of damage done to the laminates as a result of the impact. IITRI's ultrasonic scanning and recording equipment was used to nondestructively inspect the various test specimens.

Figure 15 shows the overall setup of the ultrasonic scanning and recording system used in this program. The ultrasonic transducer system is operated by a Model 5052UA pulser-receiver manufactured by Panametrics, Inc. It is capable of driving the transducers in either the pulse-echo or through-transmission mode. The pulser-receiver is a broad-band device which can readily operate transducers in the range of 1 to 20 MHz. It has independent controls for input energy, signal repetition rate, high pass filter gain, and attenuation all of which control the final transducer signal. It provides a time domain output for reviewing the RF signal on an oscilloscope or spectrum analyzer. It also has a gated peak output detector which can operate one axis of an x-y recorder pen for plotting the ultrasonic information contained in the variation of the peak output signal.

In addition to the transducers and pulser-receiver, three pieces of equipment were required to get a complete picture of specimen integrity. They were an x-y recorder, an oscilloscope, and an oscilloscope camera.

The x-y plotter was a HP-7044A x-y recorder. The x and y control sensitivities ranged from 0.25 mV/cm to 5 V/cm. The recorded C-scan could be smaller, equal to, or larger than the actual specimen up to a size of 25 x 38 cm (10 x 15 in.). The x-y recorder could operate in either the pen-lift or analog mode. In the pen-lift mode, the output from the peak detector was channeled through an electronic alarm unit into the pen-lift control of the recorder. The alarm unit was set to trigger the pen-lift whenever the amplitude of the peak detector fell below a prescribed level, indicating a flaw;

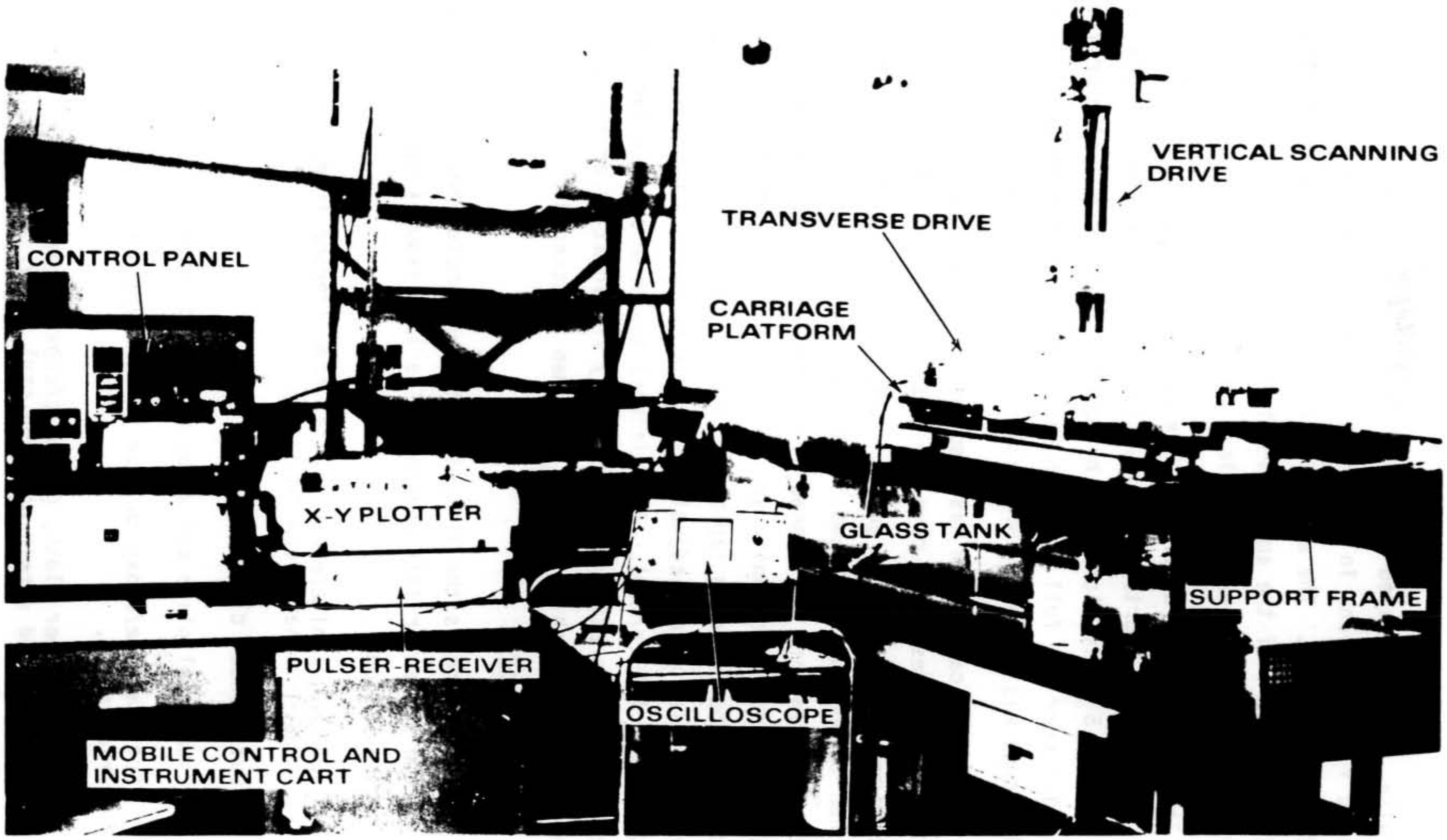


Figure 15. Ultrasonic scanning and recording system for nondestructive flaw detection in composite laminates.

otherwise, the pen stayed in contact with the paper tracing line. This gave detailed flaw locations in the plane of the specimen with definite outlines of the flaw boundaries. The analog mode supplements this information by giving a continuous record of the amplitude of the gated pulse. It is obtained by scanning the specimen with the alarm unit by-passed.

The oscilloscope used was a Tektronix Model 445/A2/B2. This was a 50 MHz, dual channel, portable oscilloscope with deflection factors calibrated from 5 mV to 5 V/division. The horizontal deflection system provides stable triggering over the full bandwith capabilities of the vertical system. The oscilloscope was fed with information processed by the pulser-receiver.

The mechanical system has a scanning carriage platform with three precision screw drives which move the ultrasonic transducer along three mutually perpendicular axes. It is guided along the tank length on steel shafts attached to the support frame. The platform is elevated above the tank and can be traversed and positioned at any tank location. A motorized screw drives the vertical scanning arm which holds the ultrasonic transducer at the lower end. The drive is capable of moving the vertical arm in up and down scanning strokes of any adjustable length up to 35.6 cm (14 in.) at rates up to 127 cm/min (50 in/min). A horizontal traverse screw drive is also present. It is manually operated and is used only for locating or focusing the ultrasonic transducer each time a new specimen is scanned.

2.3 TEST SEQUENCE

The following is the list, in order of completion, of the steps used to conduct the tests for this program. The list assumes completion of the strain gage encapsulations.

- Remove graphite/epoxy prepreg from storage freezer (allow to warm to near room temperature).
- Cut bleeder cloth to size.
- Clean caul plate and spray with mold release.
- Cut graphite/epoxy to size for correct laminate orientation.
- Layup bleeder cloth, graphite/epoxy plies, and encapsulated strain gages on caul plate.

- Form vacuum bag with nylon film and flexible adhesive tape.

- Insert vacuum bagged layup into curing oven.

- Cure specimen according to schedule described in Section 2.1.1.

- Allow layup to cool to room temperature, remove from vacuum bag, and trim edges of laminate with scalpel, etc.

- Nondestructively inspect laminate noting strain gage locations and any fabrication defects. Quantify defects if possible.

- Adhesively bond laminate to aluminum frames using torqued bolts to control compression. Allow adhesive to cure and remove bolts.

- Solder embedded gage ribbon leads to extension lead wires.

- Prepare surfaces of graphite/epoxy laminate and bond surface strain gages. Attach lead wires to surface gages. Check working condition of all gages using multimeter to read gage resistances. Mark defective embedded gages as such, and replace defective surface gages as required. Adhesively bond accelerometer to the back surface of the target specimen as close to the point of impact as possible.

- Prepare drop test fixture. Position and center specimen platform under guide rods. Mount specimen on platform, and locate clamping blocks. Turn leg bolts until specimen is level and snugged up against lower guide rod mounting bracket. Move impactor to desired drop height and clamp.

- Attach strain gage lead wires to potentiometric circuit of data recording system. Connect accelerometer cable to charge amplifier.

- Turn on digitizer and computer hardware. Load impact test data transfer software into the micro-computer. Check data storage disc for adequate storage space. Replace disc as required.

- Start impact test control program. Turn on charge amplifier to accelerometer. Set sensitivity controls on digitizer, i.e., amplitude voltage, data points per sec, triggering mode, etc.

- Without dropping the impactor, test the triggering sensitivity several times to ensure "hair triggering" of the digitizer.

- Start data gathering program. Key in number of channels being recorded, maximum of eight.

- Check digitizer to ensure that "pre-trigger" light is illuminated. This light indicates that the digitizer is ready to record data when triggered by the accelerometer. If light is not illuminated, restart test control program.

- Recheck all power and control setting switches.

- Spray lubricant onto guide rods.

- Release impactor and allow to fall onto target. Capture impactor after first rebound, before second impact.

- Data capture and transfer to the microcomputer are automatically handled by the test software.

- Transfer impact data from microcomputer to storage disc using data transfer program.

- Remove test specimen from specimen platform. Disconnect strain gage lead wires from potentiometric circuit and accelerometer cable from charge amplifier.

- Remove surface bonded strain gages and accelerometer from target specimen. Leave embedded gage lead wires intact for repeat tests if necessary.

- With aluminum plates in place, nondestructively inspect the test specimen. The specimen should be ultrasonically inspected using a 5 MHz, compression wave, immersion, focused transducer operated in the pulse-echo mode generating analog or pen-lift C-scans.

- If multiple tests are to be conducted, bond new surface strain gages onto the specimen and retest.

- Read strain data off data storage disc into smoothing and/or plotting program. Final result is to plot one to seven strain curves with associated acceleration curve on a single plot to show comparative strain histories for a single impact event as a function of position with respect to the impact location.

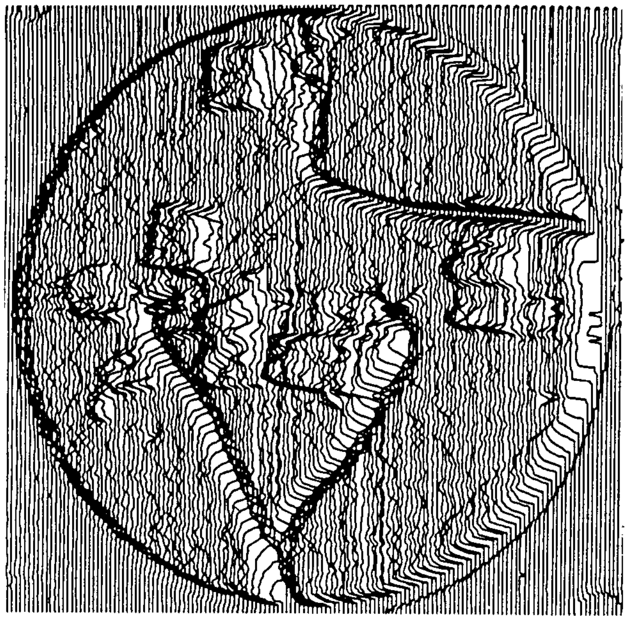
- Make correlation between strain data and impact damage.

3. RESULTS

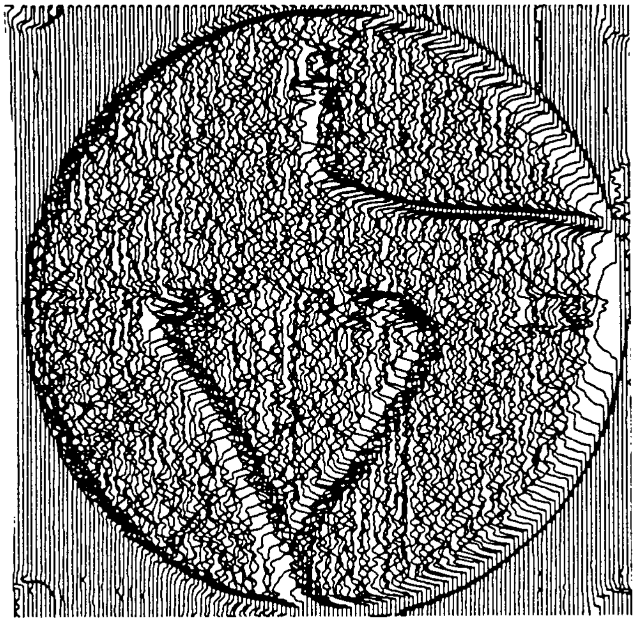
Specimen A5-2 was a $[45/0/-45/90]_s$ specimen with a gage layout as shown in Figure 6. The specimen was scanned ultrasonically before impact using a 5 MHz transducer in the pulse-echo mode. Two analog C-scans are shown for this specimen in Figure 16, one with the gate monitoring the back face reflection and the other with the gate monitoring the ultrasonic pulse at the midsurface of the specimen. The embedded gages and their leads are clearly evident. Transient strain results obtained during impact from various surface and embedded gages are shown in Figures 17 and 18. Figure 17 shows that the surface strain on the back face opposite the point of impact increases at a fast rate reaching the separation limit of the instrument. The next two gages on the back surface away from the central point show a large dropoff in the strain. The embedded gages, which in this case were placed at the midsurface show a relatively low, but constant, strain indicating that the membrane component of the deformation is relatively small and is maintained constant throughout the impact. Ultrasonic scans of the specimen after impact are also shown in Figure 16 for the monitoring gate at the back face and the midsurface of the specimen. These scans cannot be interpreted easily because of the presence of the embedded gages. However, it is seen that the only evidence of damage is concentrated near the point of impact as corroborated by the strain data.

Specimen A6-1 was a replicate of the previous specimen, but with a different gage layout as shown in Figure 7. Analog ultrasonic C-scans before impact are shown in Figure 19 for the monitoring gate at the back face and at the midsurface, respectively. Transient strain results obtained during impact from various surface and embedded gages are shown in Figure 20. All strain records indicate the presence of a flexural stress wave near the point of impact of approximately 100 μs duration. Peak strains as large as 0.006 are shown, sufficient to cause matrix cracking. It is not known whether the constant strain levels indicated beyond 100 μs are indeed steady-state strains or a gage/instrumentation malfunction. Further testing would be required to

Before Impact

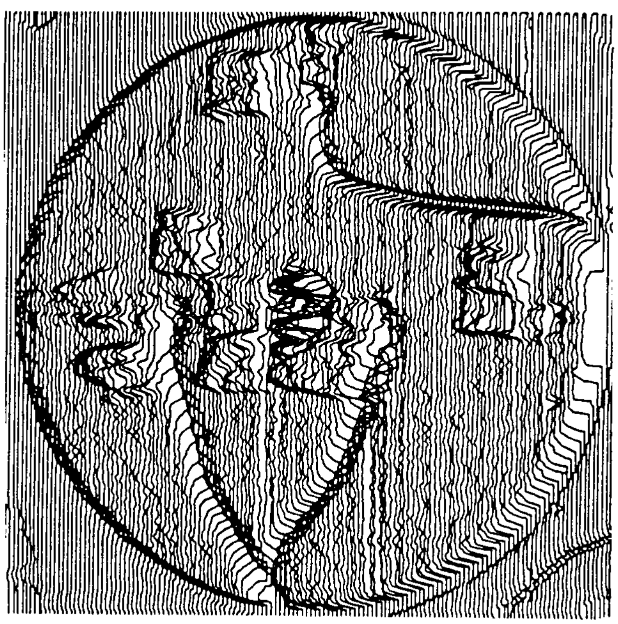


Gate at Back Face

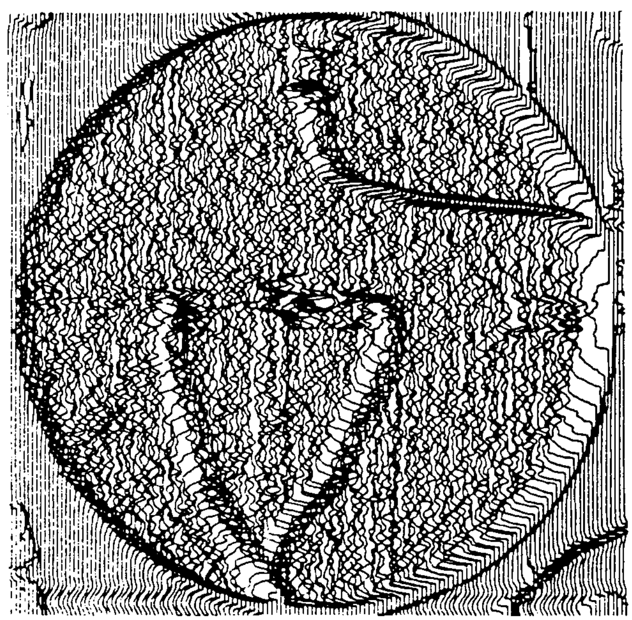


Gate at Mid-Thickness

After Impact



Gate at Back Face



Gate at Mid-Thickness

Figure 16. Analog ultrasonic C-scans for $[45/0/-45/90]_s$ laminate before and after impact with 185 gm impactor from 120 cm height. (Specimen A5-2)

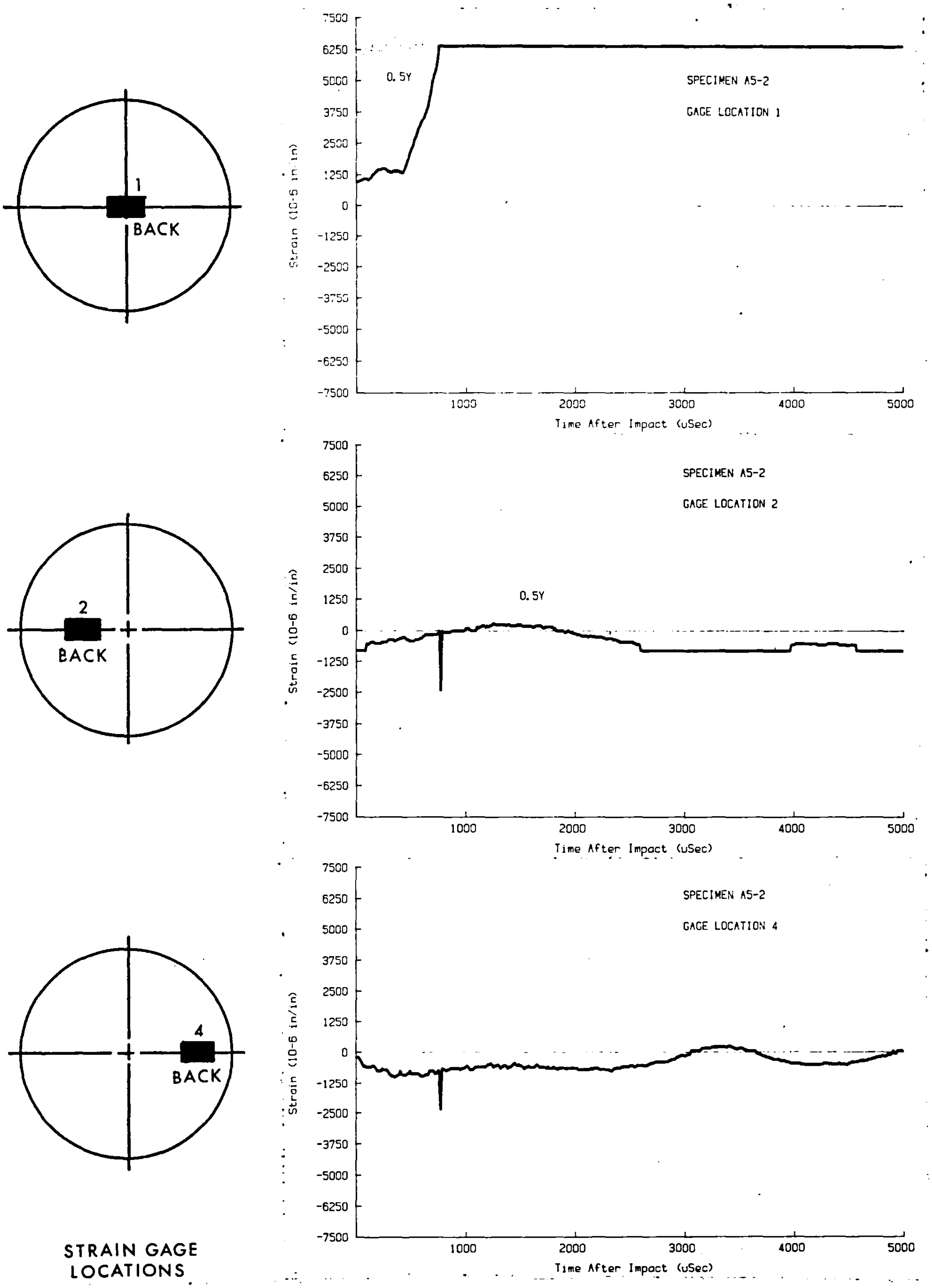


Figure 17. Transient strains in $[45/0/-45/90]_s$ laminate after impact of a 185 gm impactor from a height of 120 cm. (Specimen A5-2)

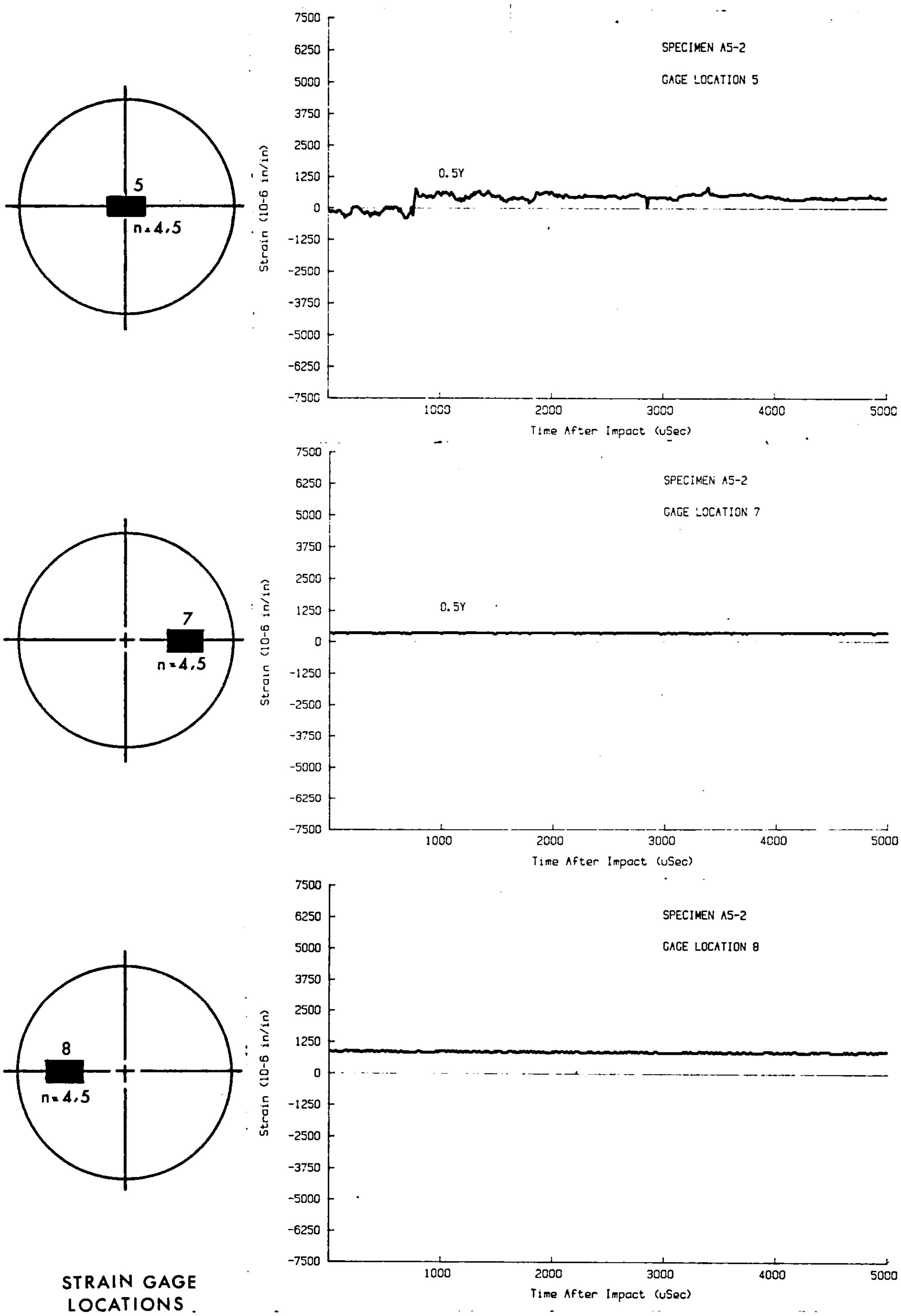
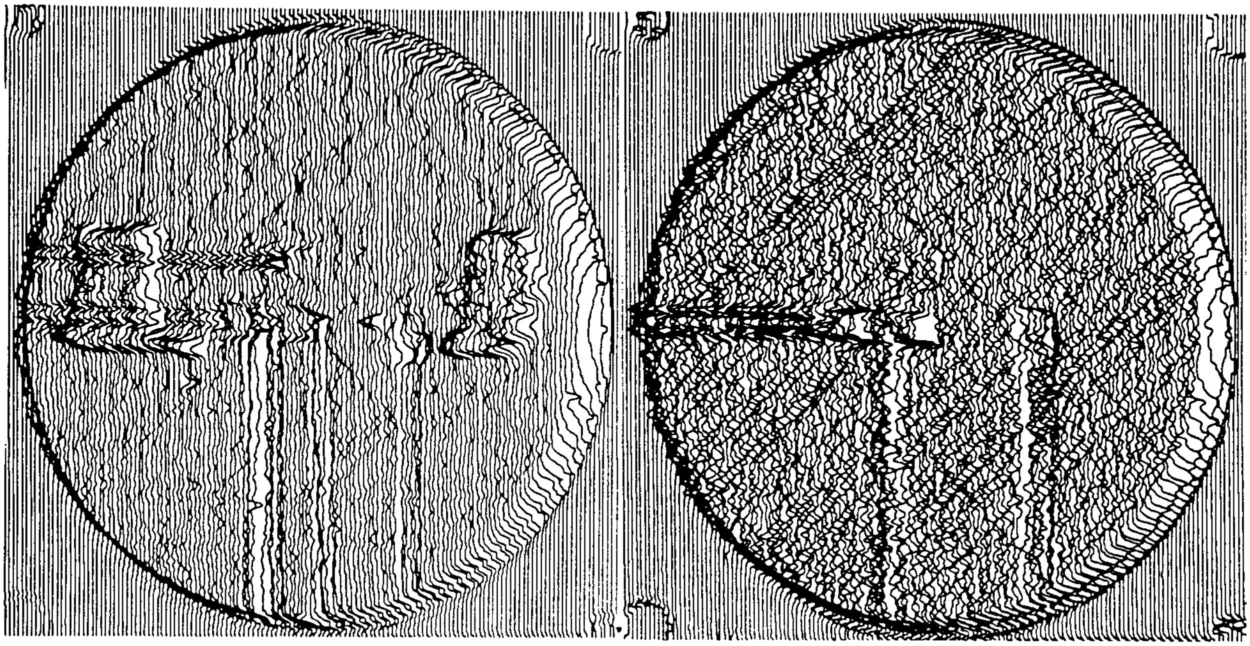


Figure 18. Transient strains in $[45/0/-45/90]_s$ laminate after impact of a 185 gm impactor from a height of 120 cm. (Specimen A5-2)

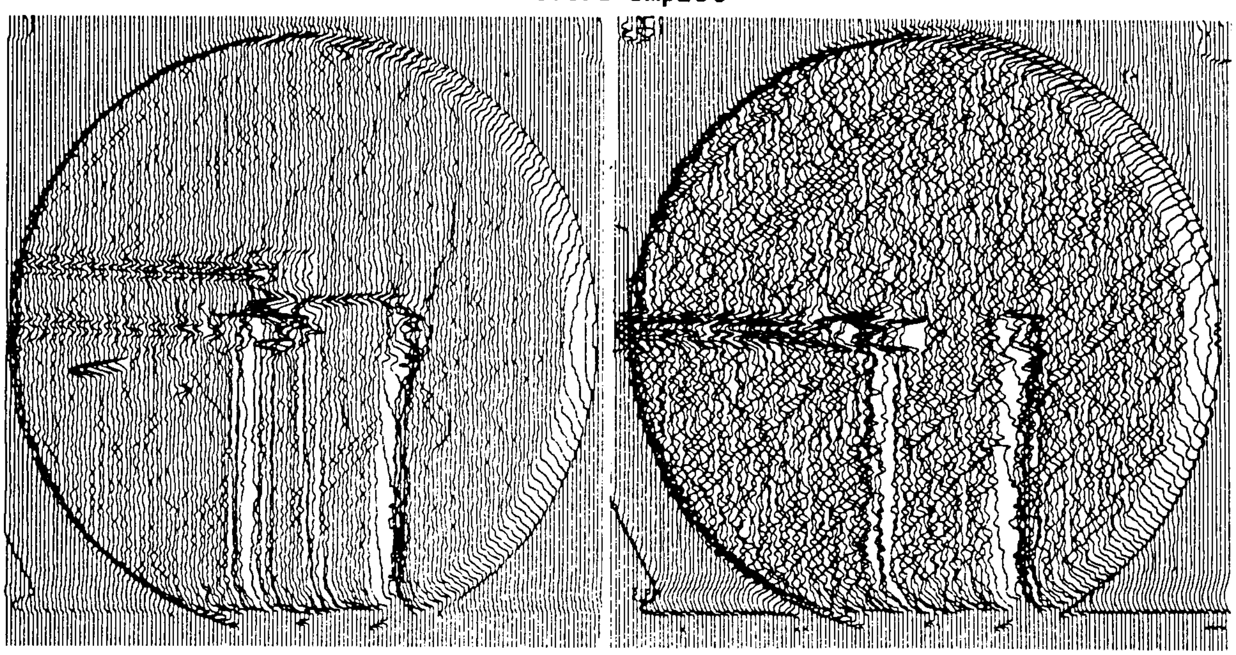
After Impact



Gate at Back Face

Gate at Mid-Thickness

Before Impact



Gate at Back Face

Gate at Mid-Thickness

Figure 19. Analog ultrasonic C-scans for $[45/0/-45/90]_s$ laminate before and after impact with 185 gm impactor from 120 cm height. (Specimen A6-1)

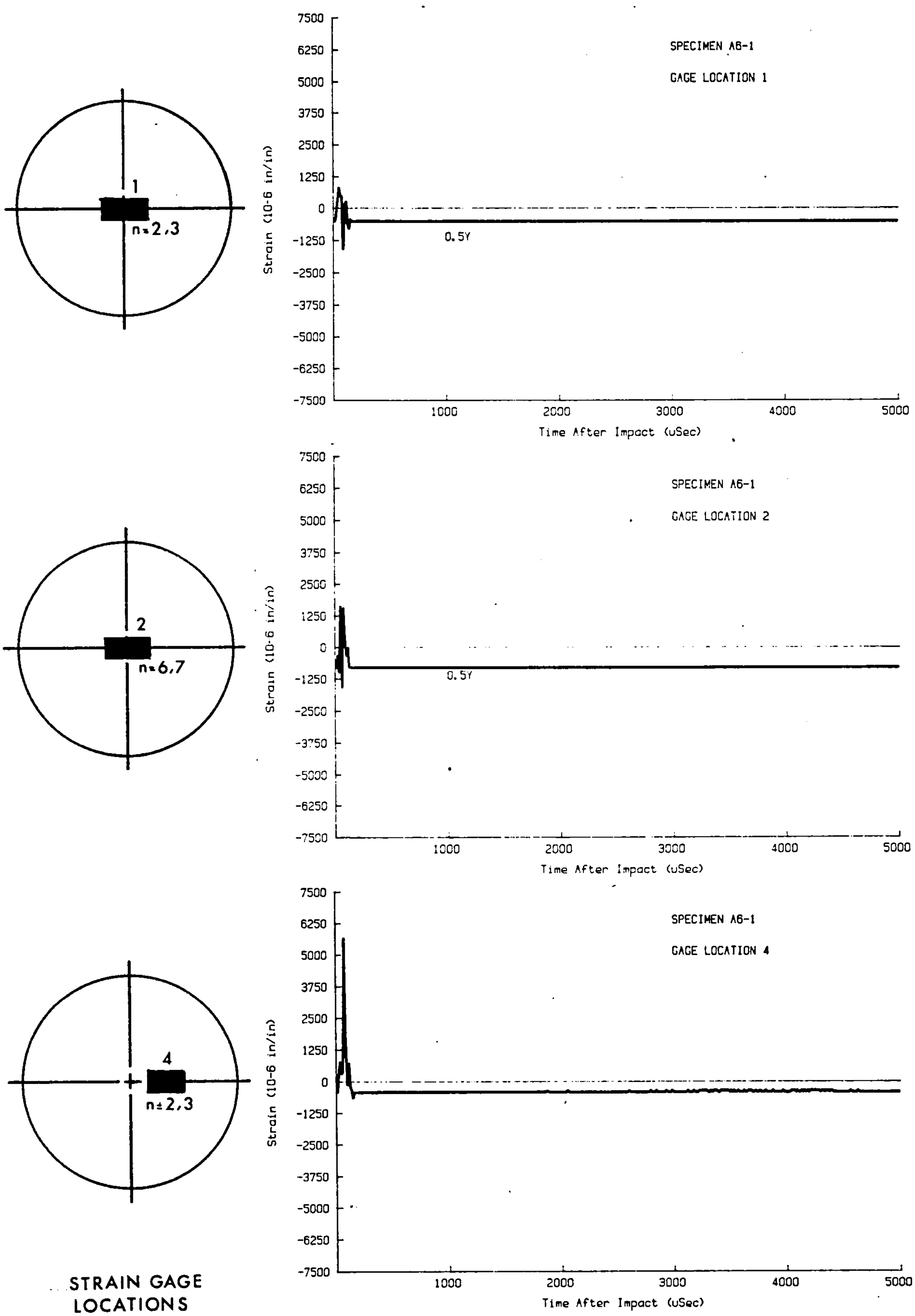


Figure 20. Transient strains in $[45/0/-45/90]_s$ laminate after impact of a 185 gm impactor from a height of 120 cm. (Specimen A6-1)

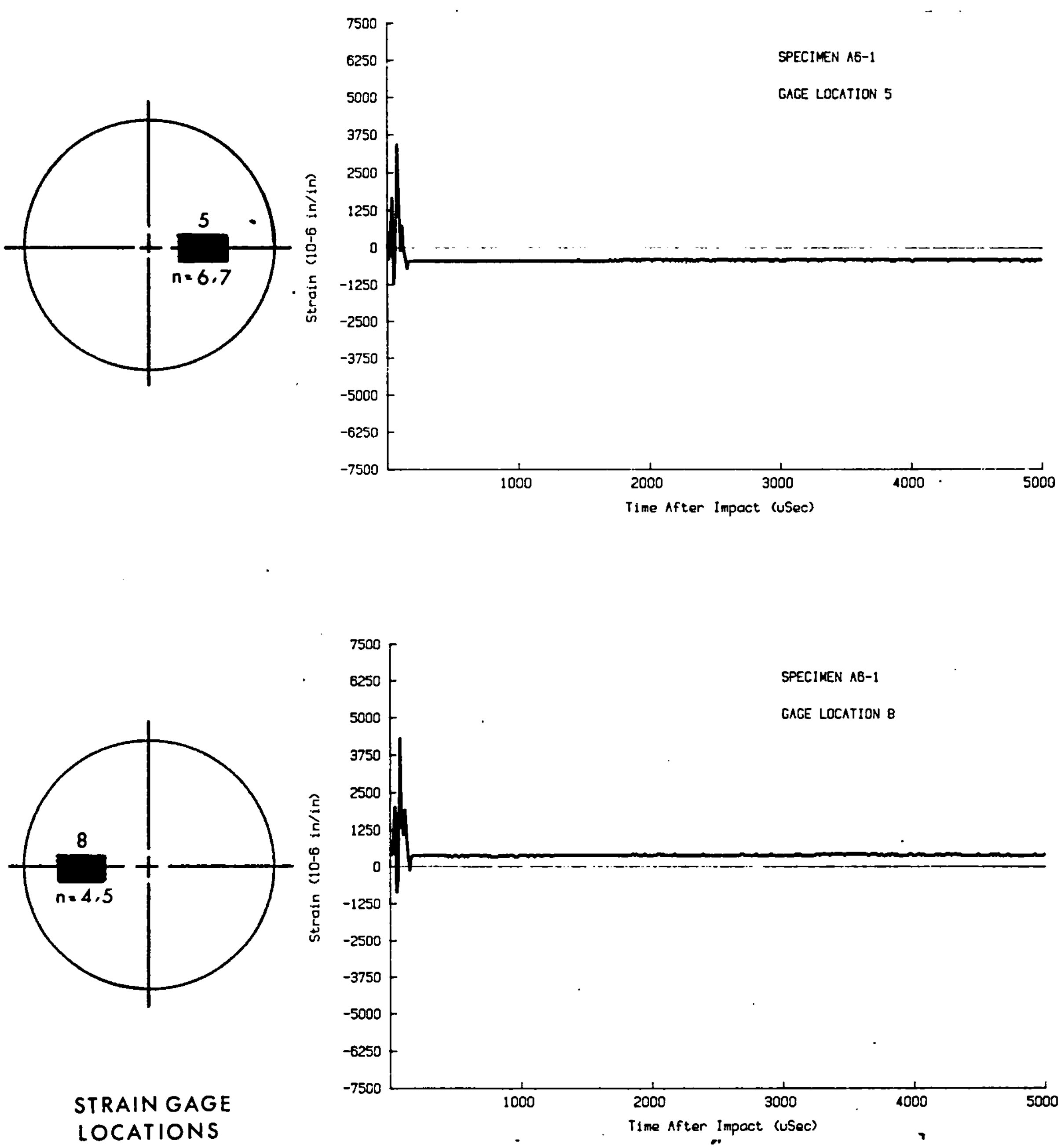


Figure 20. (Con't) Transient strains in $[45/0/-45/90]_s$ laminate after impact of a 185 gm impactor from a height of 120 cm. (Specimen A6-1)

identify and separate the stages of wave propagation and steady-state, quasi-static response. Ultrasonic analog C-scans of the specimen after impact are shown in Figure 19, with the monitoring gate at the back face and at the mid-surface. The former of the two scans shows evidence of damage concentrated near the point of impact and, because of the gate location, near the back face.

Specimen B5-1 was a 16-ply quasi-isotropic specimen of $[45/0/-45/90]_{2S}$ layup with a gage layout as shown in Figure 8. Analog ultrasonic C-scans before impact are shown in Figure 21, with the monitoring gate at the back face and at the midsurface. Transient strain records obtained from various surface and embedded gages are shown in Figures 22 and 23. The back surface gage at location 1 reaches the saturation point at a strain level of 6250 $\mu\varepsilon$. The back surface strain near the point of impact (Figure 22) reaches a low peak at approximately 1 ms after impact. Embedded gages under and near the point of impact show similar response. Gage 10 located at the midsurface 1 in. from the point of impact, does not show any response, possibly because the membrane component of deformation is negligible for the thicker 16-ply laminate. Analog C-scans of the specimen after impact are shown in Figure 21, with the gate at the back face and midsurface. Here the evidence of damage is seen only in the latter of the two scans, possibly indicating that the damage was more concentrated near the midsurface.

Specimen B6-1 was a replicate of the specimen above with a different gage layout (Figure 9). Analog C-scans before impact are shown in Figure 24, with the monitoring gate at the back face and the midsurface. Transient strain records obtained from surface and embedded gages are shown in Figure 25. Most embedded gages show very little response, except the gage at location 2 which apparently failed. Analog C-scans after impact are shown in Figure 24, with the gate at the back face and the midsurface. Both of these scans reveal damage near the point of impact.

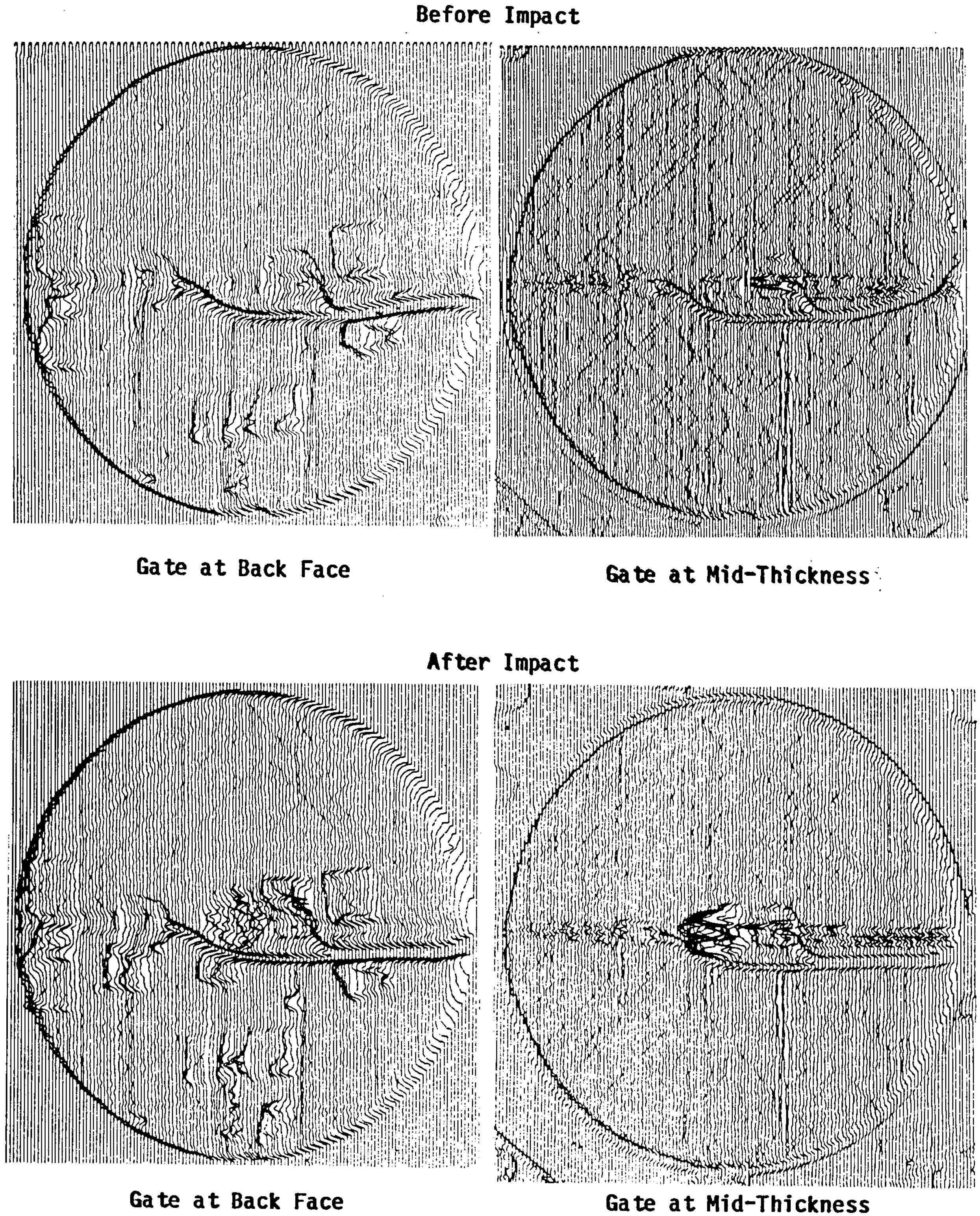


Figure 21. Analog ultrasonic C-scans for $[45/0/-45/90]_{2s}$ laminate before and after impact of a 185 gm impactor from 165 cm height. (Specimen B5-1)

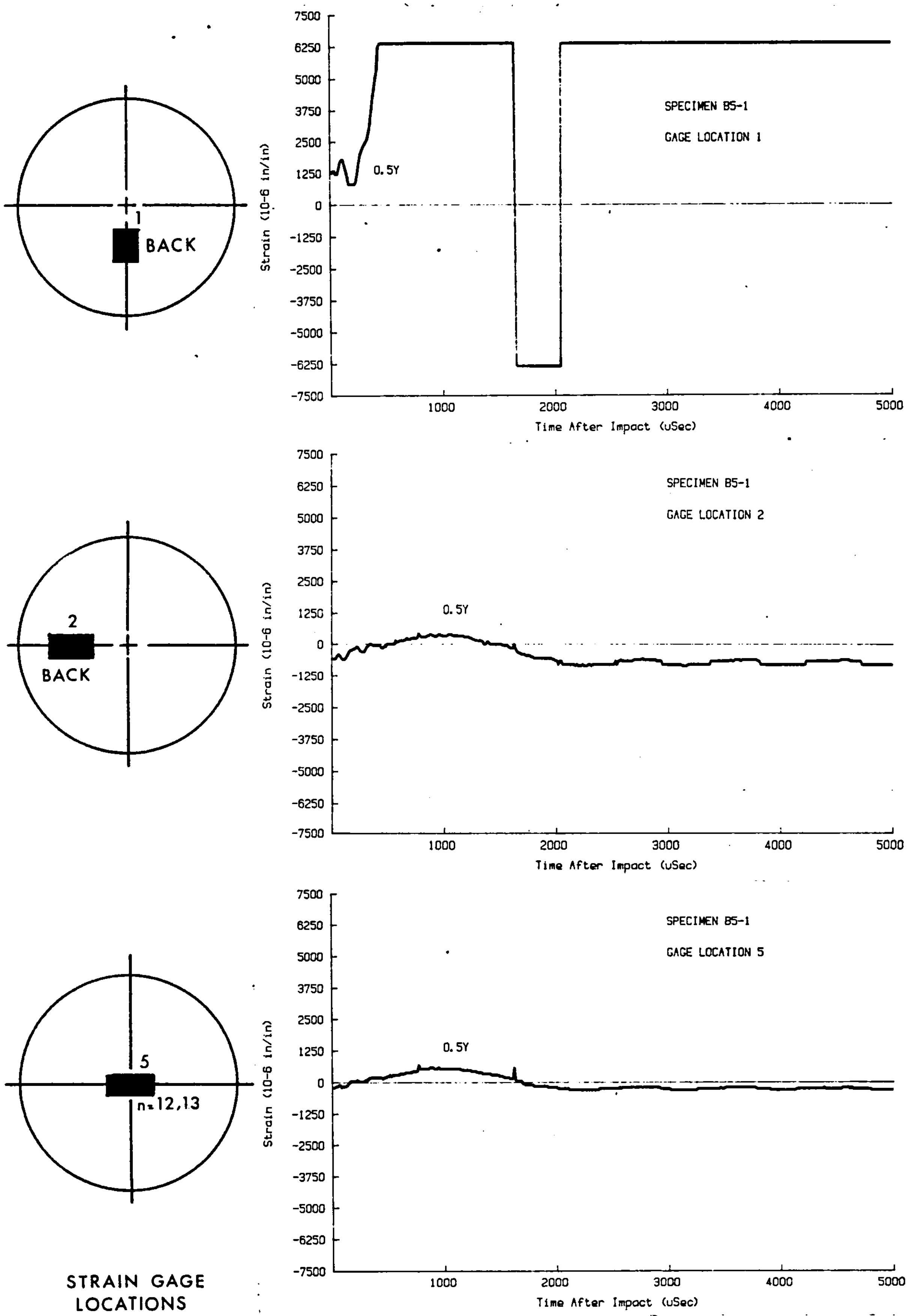


Figure 22. Transient strains in $[45/0/-45/90]_{2s}$ laminate after impact of a 185 gm impactor from a height of 165 cm. (Specimen B5-1)

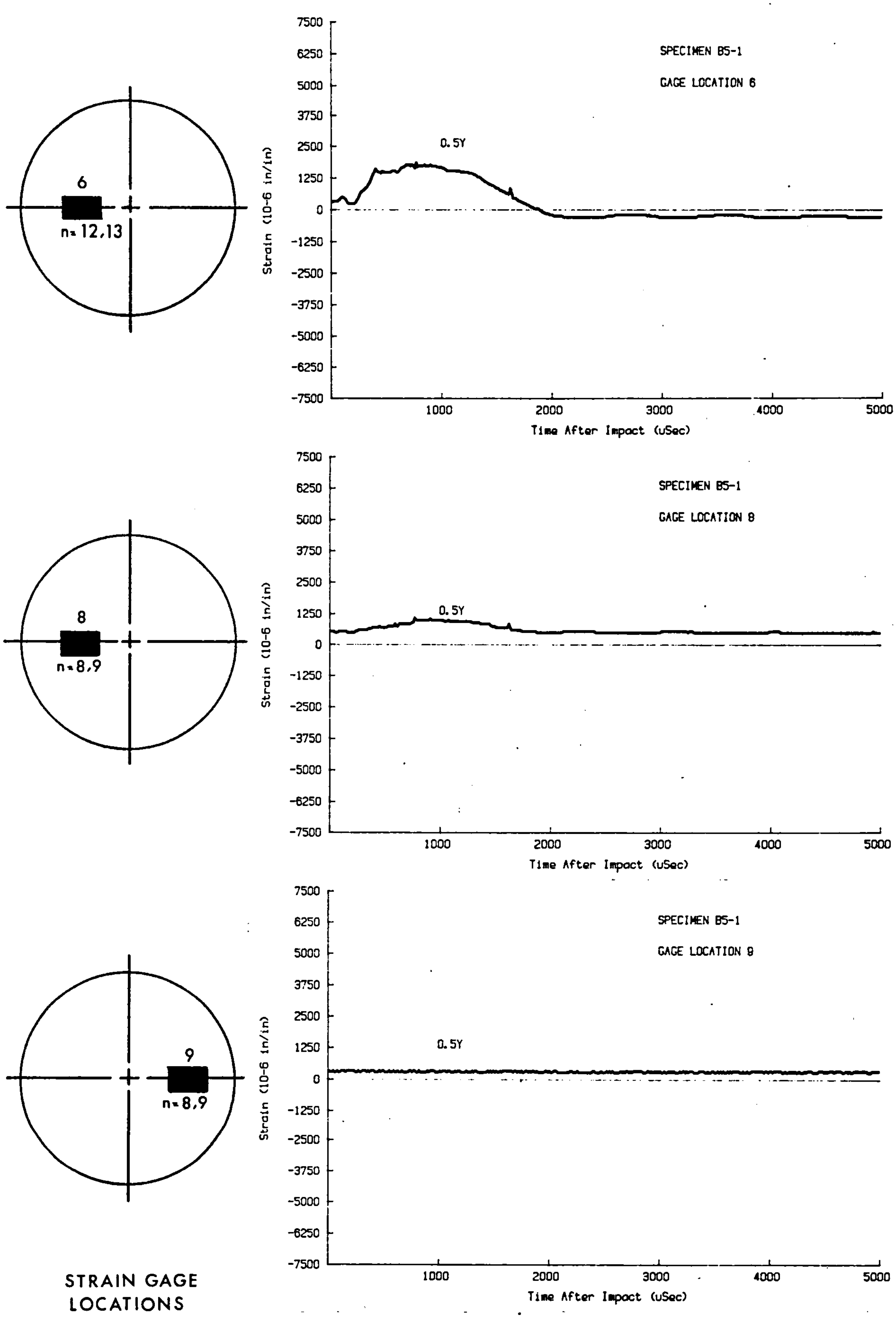
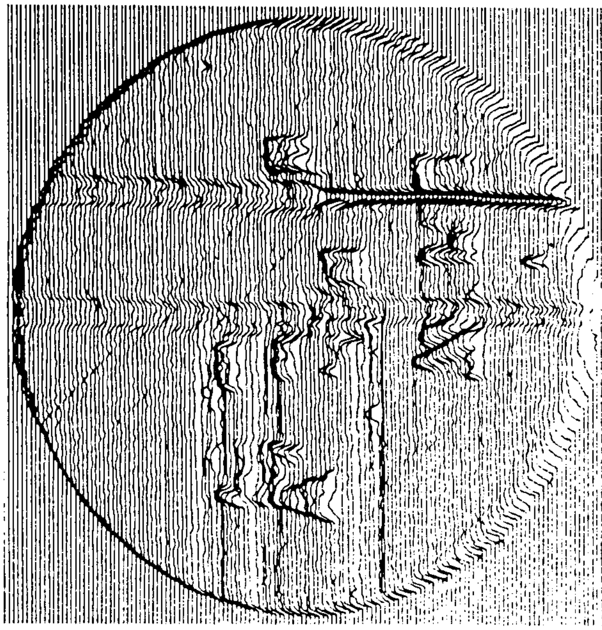
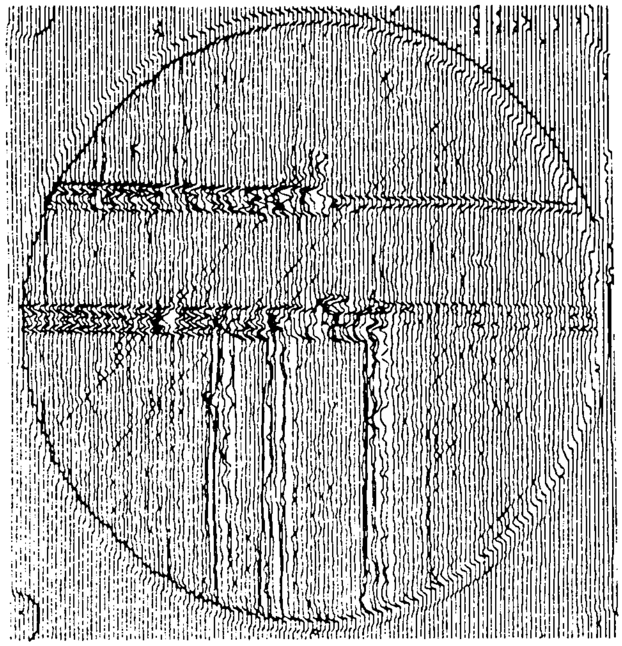


Figure 23. Transient strains in $[45/0/-45/90]_{2s}$ laminate after impact of a 185 gm impactor from a height of 165 cm. (Specimen B5-1)

Before Impact

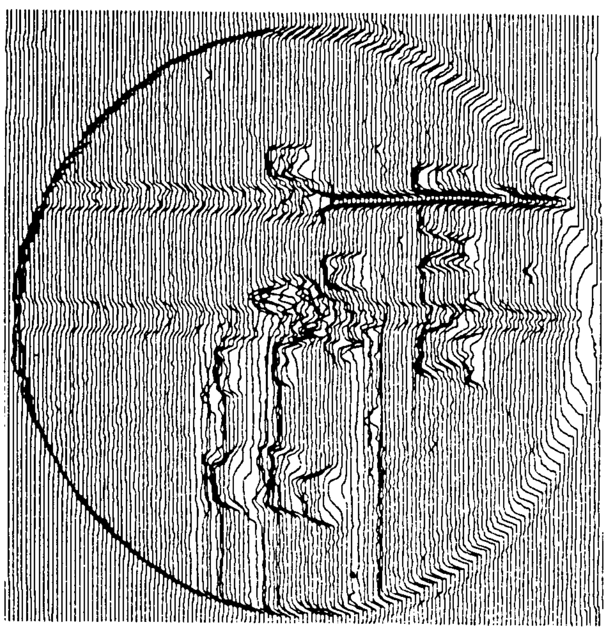


Gate at Back Face

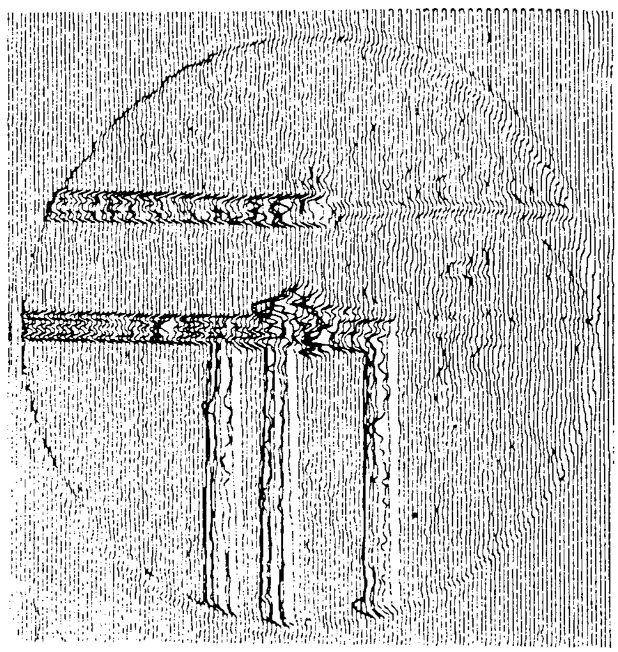


Gate at Mid-Thickness

After Impact



Gate at Back Face



Gate at Mid-Thickness

Figure 24. Analog ultrasonic C-scans for $[45/0/-45/90]_{2s}$ laminate before and after impact of 185 gm impactor from 165 cm height. (Specimen B6-1)

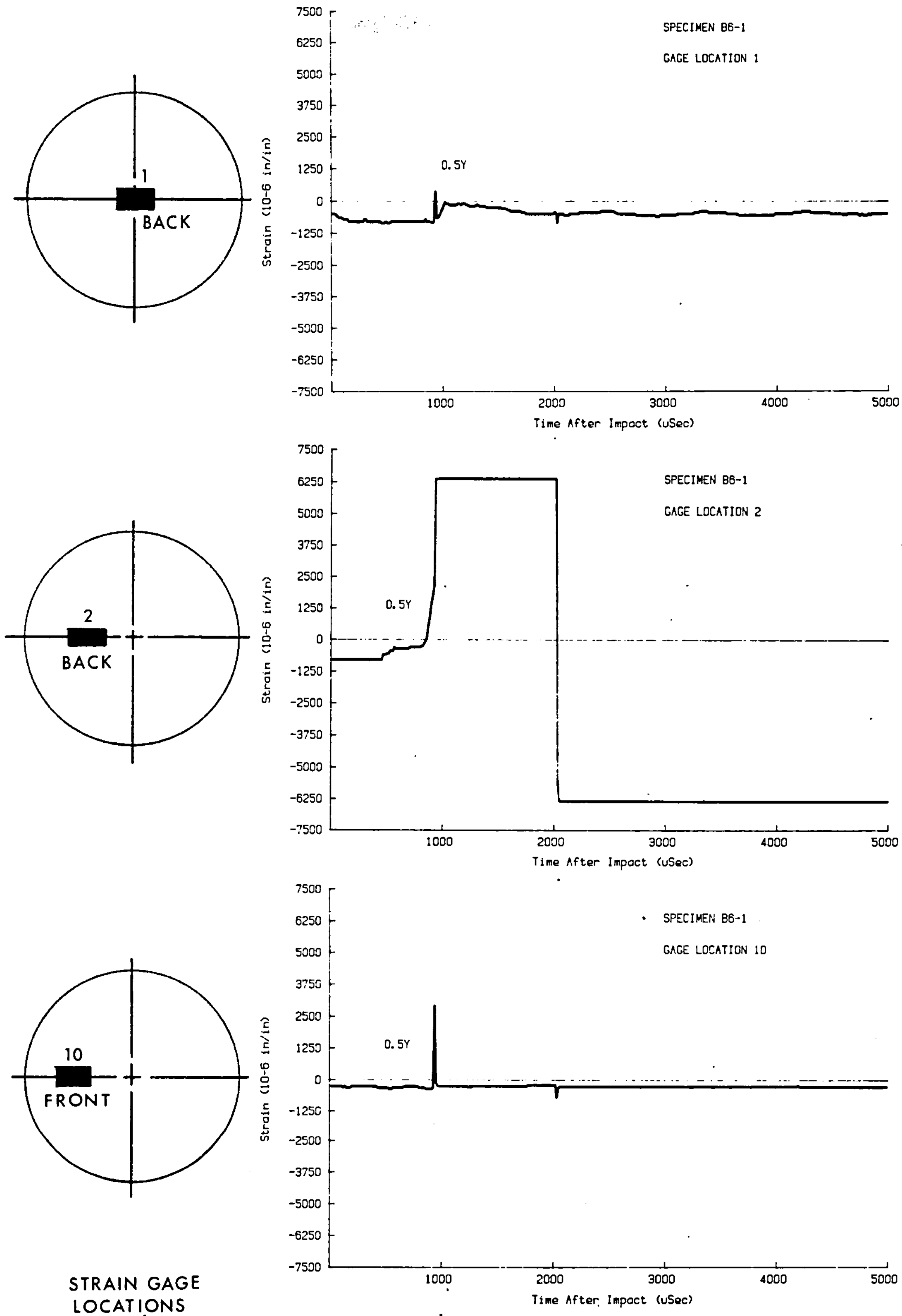


Figure 25. Transient strains in $[45/0/-45/90]_{2s}$ laminate after impact of a 185 gm impactor from a height of 165 cm. (Specimen B6-1)

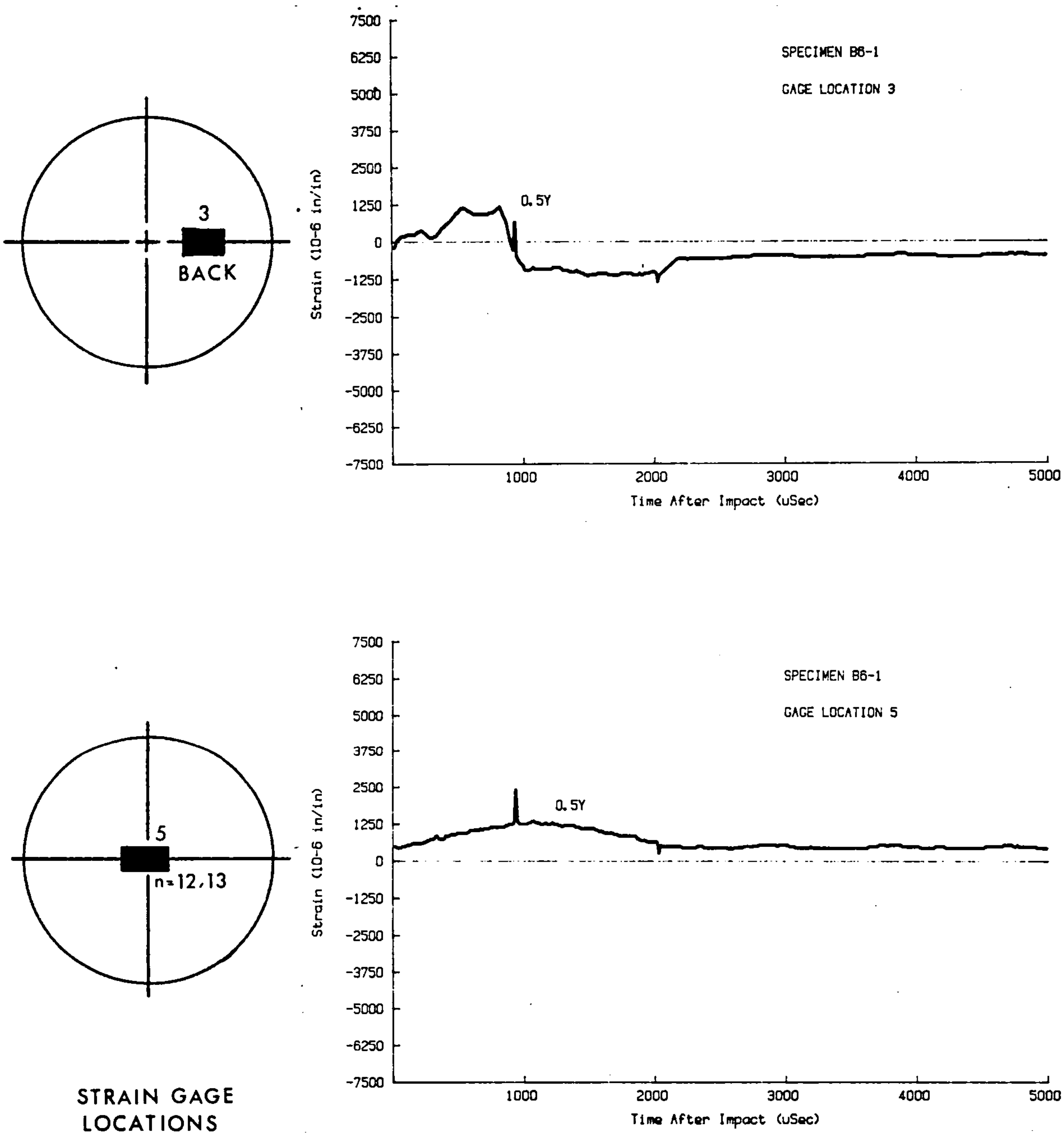


Figure 25. (Con't) Transient strains in $[45/0/-45/90]_{2s}$ laminate after impact of a 185 gm impactor from 165 cm height. (Specimen B6-1)

4. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Impact studies were conducted on 8-ply and 16-ply quasi-isotropic graphite/epoxy laminates, instrumented with surface and embedded strain gages. Techniques were further developed for embedding strain gages between the graphite/epoxy plies. Transient strains during impact were recorded with a waveform digitizer capable of sampling data at 0.5 μs intervals.

In most cases the embedded gages were placed at the midsurface of the specimen and thus recorded only the membrane or in-plane component of the strain. This membrane component was much smaller for the thicker laminate as expected. In most cases the duration of impact was approximately 2 ms with strain peaks reaching approximately 1 ms after impact. In one case (Specimen A6-1) considerable flexural oscillation was recorded in the first 100 μs after impact. Recorded strains were large enough to cause matrix cracking, but not fiber fracture.

The damage induced was inspected by ultrasonic scanning before and after impact. Analog C-scans were obtained with the monitoring gate at the back face and midsurface of the specimen. Although the presence of embedded gages obscured the C-scans, damage was always detectable. This damage was localized near the point of impact. In the 8-ply laminates the damage was concentrated near the back face of the specimen, whereas in the 16-ply laminates damage was detected at the midsurface as well as near the back face.

The results obtained to date are not sufficient to reach definite quantitative conclusions. Further work is necessary to study the phenomena more systematically. The reproducibility of the damage mechanisms and extent of damage should be verified first. Then, it will be possible to study various aspects of the problem by using more specimens. First, nondestructive inspection before and after impact should be conducted on specimens without strain gages, because the presence of gages obscures the ultrasonic scans. The location of strain gage embedment in subsequent similar specimens should be determined on the basis of the damage indications of the ultrasonic inspection. To minimize fracture of the strain gage grid when matrix cracking occurs, small

gages should be used in place of large gages. Ultrasonic C-scans should be complemented by A-scans in order to determine the through-the-thickness location of the damage. X-radiography or holographic interferometry could be used as supplements or alternatives to ultrasonic inspection. The relative magnitudes of the membrane and flexural deformations should be varied by varying the specimen diameter for a fixed laminate thickness. Both the short-time and long-time response of the plate should be determined. The initial wave propagation stage is of short duration (on the order of microseconds), whereas the quasi-static response is of at least two orders of magnitude longer duration. The through-the-thickness deformation should be investigated by means of thick beam specimens instrumented on the edges. Crack detection instrumentation can be used to supplement strain gage data.

The type and extent of damage should be correlated with the imparted energy as determined from the acceleration of the impactor. The damage growth under repeated impacts should be measured and the accumulation of damage related to the total imparted energy. The energy absorbing capabilities of several basic types of matrix, the standard 3501-6 (Hercules) resin and the more ductile polysulfone and polyether-etherketone (PEEK) resins, should be compared. Additionally, quasi-isotropic laminates and more anisotropic lay-ups, such as $[45/0/-45/0]_s$, should be investigated.

Residual stiffness and strength of laminates subjected to impact should be measured and compared with the stiffness and strength of the undamaged material. Whenever possible, experimental results should be compared with analytical predictions.

REFERENCES

1. Foreign Object Impact Damage to Composites, ASTM, STP 568, 1975.

2. C. T. Sun and R. L. Sierakowski, "Recent Advances in Developing FOD Resistant Composite Materials," Shock and Vibration Digest, Vol. 7, No. 2, February 1975.

3. F. C. Moon, "A Critical Survey of Wave Propagation and Impact in Composite Materials," NASA CR-121226, May 1973.

4. A. Wrzesien, "Improving the Impact Resistance of Glass-Fiber Composites," Composites, Vol. 3, pp. 172-175, 1972.

5. C. A .Ross and R. L. Sierakowski, "Studies on the Impact Resistance of Composite Plates," Composites, Vol. 4, pp. 157-161, 1973.

6. L. A. Friedrich and J. L. Preston, "Impact Resistance of Fiber Composite Blades Used in Aircraft Turbine Engines," NASA CR-134502, May 1973.

7. I. M. Daniel and T. Liber, "Wave Propagation in Fiber Composite Laminates," NASA CR-135086, June 1976.

8. C. T. Sun, "An Analytical Method for Evaluation of Impact Damage Energy of Laminated Composites," Composite Materials: Testing and Design (Fourth Conference), ASTM STP 617, pp. 417-440, 1977.

9. I. M. Daniel, T. Liber and R. H. LaBedz, "Wave Propagation in Transversely Impacted Composite Laminates," Experimental Mechanics, Vol. 19, pp. 9-16.

10. D. E. Petit, "Residual Strength Degradation for Advanced Composites," Interim Quarterly Report LR 28360-2, Lockheed California Co., February 1978.

NASA Contractor Report 172227
Distribution List
NAS1-16763

	No. Copies
NASA Langley Research Center Hampton, VA 23665 Attn: Research Information Office, Mail Stop 151A	2
Walter Illg, Mail Stop 188E	12
NASA Ames Research Center Moffett Field, CA 94035 Attn: Library, Mail Stop 202-3	1
Dryden Flight Research Facility P. O. Box 273 Edwards, CA 93523 Attn: Library	1
NASA Goddard Space Flight Center Greenbelt, MD 20771 Attn: Library	1
NASA Lyndon B. Johnson Space Center 2101 Webster Seabrook Road Houston, TX 77058 Attn: JM6/Library	1
NASA Marshall Space Flight Center Marshall Space Flight Center, AL 35812 Attn: Library, AS24L	1
Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91103 Attn: 111-113/Library	1
NASA Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135 Attn: Library, Mail Stop 60-3	1
NASA John F. Kennedy Space Center Kennedy Space Center, FL 32899 Attn: Library, NWSI-D	1
National Aeronautics and Space Administration Washington, DC 20546 Attn: RTM-6	1
NASA Scientific and Technical Information Facility 6571 Elkridge Landing Road Linthicum Heights, MD 21090	22 plus original